University of Alberta

Copper Mine Tailings Reclamation With Biosolids

By

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in
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I. LITERATURE REVIEW

1. INTRODUCTION

Mining is an important part of the Canadian economy providing 39 billion dollars of gross domestic product in 2002 (Natural Resources Canada 2002). This profit, however, does not come without costs. In Canada mining has disturbed approximately 0.04 million hectares of land (Natural Resources Canada 2002). Land disturbed by mining is often negatively impacted chemically, physically and biologically, which can limit the ability of these areas to sustain plant growth. Without intervention these areas remain barren for long periods of time and can result in considerable soil loss by wind and water and possible contamination to surrounding areas. Reclamation, which can be defined as "the construction of topographic, soil, and plant conditions after disturbance, which may not be identical to the predisturbance site, but which permits the degraded land mass to function adequately in the ecosystem of which is was a part" (Munshower 1994) is an important component of the mine industry in Canada. Lands disturbed by mining activities in Canada are now required to be reclaimed to established standards which are set on a provincial basis.

Disturbed land will usually naturally reclaim itself over time. The process to facilitate the necessary edaphic and biological changes is slow and occurs through a series of plant successional stages that depend on the level of disturbance, the resulting spoil material left as the root zone and climate (Munshower 1994). However, land disturbed by mining is subject to various regulations and companies are responsible for returning this land to a productive state in a timely fashion. Therefore, one of the main goals of reclamation is to achieve a sustainable plant community on a disturbed site in a short time period. To achieve this goal, time, energy and often the addition of various amendments are required to speed up the successional process.

One common amendment is inorganic fertilizer, which can help increase the required nutrients in spoil material thereby increasing plant growth. However, inorganic fertilizers only adjust soil chemical imbalances and do not directly alter soil physical or biological characteristics. Over time the establishment of vegetation on a site may help to modify these properties. Organic amendments, such as manure and biosolids, have been used to help speed soil and plant development processes by favourably altering chemical, physical and biological properties of the spoil. Biosolids or stabilized sewage sludge, is considered an excellent reclamation tool as it contains organic matter, high levels of available nutrients and increases plant growth on areas disturbed by mining activities (Sopper 1993). Biosolids, however, also contain metals, pathogens and dioxins, which can have a negative impact on site sustainability and potential end land use.

In Canada, lands disturbed by mining must be reclaimed to an approved end land use. Often this end land use involves grazing by domestic livestock or by wildlife. The impact on forage quality and possible entry into the human food chain of harmful substances that are a result of either the mining process or the amendments added to reclaim the material must be considered. Also of importance is long-term site sustainability. Reclamation practices that require limited management and produce an ecosystem that exhibits characteristics of sustainability such as energy flow, nutrient cycling and hydrologic cycling are the ultimate objective.

2. MINING

2.1 General

In 2003, the Canadian mining and mineral processing industries contributed 41.1 billion dollars to the Canadian economy (Natural Resources Canada 2002). In 2000, metal, nonmetal and fuel (coal) mining resulted in the removal of 777 million tonnes of total ore and rock quarried with approximately one third coming from metal mining operations (Natural Resources Canada 2002). Along with the removal of ore comes disturbance from associated waste rock removal and production of tailings during ore processing. In Canada the mining industry generates over one million tonnes of waste rock and 950,000 tonnes of tailings per day (Environmental Mining Council of BC 2001), resulting in large areas of disturbed land.

In British Columbia (BC), mining is the second largest industry and the land disturbed by mining has steadily grown since the late 1960s (Errington 2001). In 1969 coal and metal mines accounted for less than 1,000 ha of land but by 2000 this area had grown to over 40,043 ha (Errington 2001). At the time of his review on mining in BC Errington (2001) noted there were ten metal mines and seven coal mines operating in the province and approximately 31% of disturbed land from mining had been reclaimed. Even though reclamation efforts continue to grow the cumulative disturbance of land in BC as a result of mining activities also continues to grow as new mines are developed and closed mines require further reclamation.

Mining, especially open pit, has a significant impact on the environment. Open pit mining involves removal of ore-containing material from the bedrock by blasting, resulting in a large open pit. To extract the ore, waste rock material is removed and disturbed areas include the open pit, areas where waste rock is dumped, roads, and areas where tailings material resulting from the ore extraction is placed. Mining in BC has moved from predominately underground operations in the late 1960s to an industry that now consists mainly of large open pit mines (Errington 2001). This trend continues nationally with 76.6% of the material mined in Canada in 2000 coming from open pit mines (Natural Resources Canada 2002). The impact of open pit mining can be substantial; for example for every kilogram of copper produced up to 200 kg of waste rock can be removed and 200 kg of tailings material produced (Errington 2001). Thus to mine relatively small amounts of minerals, large areas of land have been severely disturbed and require reclamation.

In this dissertation, the term reclamation will be used to define the construction of topography, soil and plant communities after disturbance where as revegetation will account for the vegetation phase of reclamation. Reclamation refers to returning the land to a functioning condition that may not be identical to the predisturbance site while restoration implies the return of the disturbed site to the exact ecological conditions that existed prior to the disturbance (Munshower 1994). In BC, companies develop their own reclamation plans in accordance with the regulations set out by the Province. Reclamation of these disturbed mine lands is required and must be aimed at a suitable and approved end land use. In BC, over 50% of the currently reclaimed land is slated for wildlife habitat, 22% for forestry, 6% for grazing and the remaining 16% for other uses such as recreation (Errington 2001).

2.2 Tailings Ponds

Tailings are the materials that remain after the mineral ore has been removed by processing of the ore containing rock. In metal mining the ore containing rock is crushed and ground and the material then undergoes chemical processing such as floatation to remove the metal of interest. The remaining material is often pumped in a slurry to receiving ponds called tailings ponds. Tailings may also be buried or pumped into a water body, although this form of disposal has become less common due to the negative environmental impacts (Munshower 1994). During the reclamation stage, tailings ponds are drained producing a typically flat area of tailings and a small remaining water body. Tailings ponds at various mines may differ in size, texture, pH and chemical contents. Most tailings contain low amounts of organic matter and plant essential nutrients thus limiting plant establishment and growth and as a result, are highly susceptible to wind and water erosion (Norland and Veith 1995, Munshower 1994, Lavkulich 1977).

Lavkulich (1977) characterized tailings materials from nine mines across Canada according to physical, chemical, mineralogical and biological properties. He noted that chemical composition varies but in general tailings have low cation exchange capacities (CEC) and nitrogen (N) and phosphorus (P) are often limiting due to the general lack of organic matter. Bulk density was not a problem but low water storage capacity due to the coarse texture of many of the tailings was considered a severe physical limitation. Therefore, tailings material texture is important as it has a direct impact on water storage capacity. Also of importance is the pH of the material which impacts CEC and nutrient availability.

Another challenge to tailings reclamation and revegetation is the potential for these sites to be higher than normal in the mined metal. For example, at a copper (Cu) mine tailings will be higher in Cu than the surrounding soils due to the incomplete removal of copper during processing stages. These higher metal levels are often reflected in the vegetation grown on the site and can be a concern if the area is to be used by wildlife or domestic livestock (Gardner et al. 2003).

2.3 Regulations for Reclamation

In BC, reclamation of coal and hardrock mineral mines was first required in 1969 under the Mines Act. In 1979 this legislation was amended to include sand and gravel pits, coal exploration, mineral exploration and quarries (Errington 2001). In 1990 the Mines Act was amended and now includes the Health, Safety and Reclamation Code for Mines in BC (Regional Operations, Health and Safety Branch 1997). According to sections 10.7.4 and 10.7.5 of this Act "the land surface shall be reclaimed to an end land use approved by the chief inspector, that considers previous and potential uses" and " the average land capability to be achieved on the remaining lands shall not be less than the average that existed prior to mining, unless the land capacity is not consistent with the approved end land use" (Regional Operations, Health and Safety Branch 1997). The Act requires that revegetated areas be self sustaining and that the growth medium satisfies land use, capability and water quality objectives. If metal uptake is a concern, vegetation monitoring may be required and the reclamation procedure should help to "ensure that levels are safe for plant and animal life" or dealt with in an appropriate manner (Regional Operations, Health and Safety Branch 1997).

3. SOIL AND PLANT DEVELOPMENT

3.1 Soil Development

To achieve site sustainability, reclamation of a site must not only focus on establishing vegetation growth but on developing a functioning and stable soil ecosystem that exhibits proper nutrient storage and cycling, energy flow and water cycling. Soil formation is controlled by the interaction of five factors: parent material, climate, biota, topography and time (Jenny 1941). In reclamation of disturbed areas, the factors most commonly addressed are topography, biota and time with time seen as most limiting. The natural process of soil development is slow and often will not occur within a human life time; however, reclamation regulations require that a site have a self sustaining cover of vegetation.

Schafer et al. (1980) studied soil genesis in reclaimed coal mine spoils and found that within a ten year period many mine soil properties, such as electrical conductivity, soil structure and surface organic matter content, approached levels found in natural soils. However, other properties such as organic matter content at depth require very long time periods to reach equilibrium, and some properties such as texture, rock fragment content and depth to bedrock will always be different from natural soils. There is also extreme variability in how long soil development will take in a given mine site. Factors such as the nature of the spoil material remaining after mining, the climate of the area, the reclamation practices used and the ability to successfully revegetate the site will all impact the time for soil development. In their literature review, Seaker and Sopper (1988b) noted that other studies found that in mine spoils in a variety of environments, organic matter levels, soil structure and A horizon development could require from 30 to 300 years to recover. This time period included mine spoils undergoing natural succession or those being reclaimed through the use of inorganic fertilizers only.

In lands disturbed by mining low soil organic matter is a common limitation to site revegetation (Palumbo et al. 2004, Norland and Veith 1995). The addition of organic amendments hastened site recovery and ameliorated soil physical, chemical and biological limitations. Soil organic matter is generally the plant and animal residues present in the soil at various stages of decomposition but in reclamation the term soil organic matter includes any carbon assemblages such as manure, mulches, biosolids and wood chips (Munshower 1994). Chemically soil organic matter has a direct impact on CEC and acts as a plant nutrient reservoir; physically, soil organic matter influences water holding capacity, infiltration, aggregate formation and bulk density; biologically, organic matter acts as an important source of carbon and energy for soil microorganisms (Norland and Veith 1995, Seaker and Sopper 1988a). The carbon to nitrogen (C:N) ratio needs to be considered when adding organic matter as it will have a direct impact on plant available nitrogen. Different organic amendments have different C:N ratios with wood waste such as sawdust ranging from 134 to 1244:1 (Land Resource Network Ltd. 1993). Biosolids have a much lower C:N ratio due to higher nitrogen levels in the material (Epstein 2003). Biosolid C:N ratios will vary depending on the particular product and processing method used, but for biosolids produced in BC by the Greater

Vancouver Regional District a typical C:N ratio is below 20:1 (e.g. dewatered biosolids have a ratio of 7.5:1).

The addition of organic amendments to disturbed lands helps speed the process of soil formation (Seaker and Sopper 1988a and 1988b) as mine spoils lack organic matter and a microbial community (Seaker and Sopper 1988a). The addition of amendments which help to increase the microbial community, ameliorate nutrient deficiencies and improve poor soil physical properties are more effective at speeding soil development than the addition of inorganic fertilizer alone (Stroo and Jencks 1982).

3.2 Plant Establishment

The unconsolidated material that remains after mining may limit plant growth due to a variety of factors. In mining the waste material is often difficult to revegetate as it lacks organic matter and normal microbial populations, is nutrient poor, has low water holding capacity, lacks structure and is subject to erosion (Norland and Veith 1995). In metal mines, high levels of salts or heavy metals may also impede plant development. Some factors such as texture, which has a direct effect on soil aeration, water infiltration, CEC and soil erodibility, can not be readily altered by reclamation activities. Other factors such as organic matter content, CEC, soil structure and nutrient levels can be more readily altered (Munshower 1994).

For plants, the macronutrients carbon (C), N, P, potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S), and the micronutrients; iron (Fe), manganese (Mn), zinc (Zn), Cu, boron (B), molybdenum (Mo), cobalt (Co) and chlorine (Cl) are required (Brady and Weil 1996, Munshower 1994). Other elements such as arsenic (As), cadmium (Cd) and lead (Pb) are nonessential for plant growth and can result in plant toxicities or decreased plant growth if present in higher than required amounts (Kabata-Pendias and Pendias 1992). Even plant essential nutrients can result in toxicities if present in higher than required amounts.

4. BIOSOLIDS

4.1 Definition, Processing and Regulations

Biosolids can be defined as the stabilized solids that result from wastewater treatment (Epstein 2003). Wastewater treatment plants deal with both domestic and industrial sources of wastewater and the separation of the sewage sludge from the effluent and its further processing ultimately results in the product commonly referred to as biosolids. The processing of wastewater involves many steps and may differ considerably with treatment facility. The steps in a typical wastewater treatment process are outlined in Figure 1.1. After pretreatment the wastewater goes through a physical separation process termed primary treatment (Oleszkiewicz and Mavinic 2002) which results in a product known as raw sewage sludge. For the term biosolids to be used the sewage sludge must go through secondary treatment and stabilization and meet established regulatory requirements (Epstein 2003). Stabilization treatment is important as it helps reduce pathogens in the material and reduces the overall amount of material which reduces transportation costs (Sanchez-Monedero et al. 2004).

The stabilization process most often used by the Greater Vancouver Regional District (GVRD), the main producer of biosolids in BC, is anaerobic digestion. Anaerobic digestion uses microorganisms to reduce microbial biomass and in the process release methane and carbon dioxide (GVRD 1999). Anaerobic digestion can be classified as either mesophilic (36 to 38 °C) or thermophillic (48 to 57 °C). Thermophillic conditions are more efficient for pathogen reduction (Oleszkiewicz and Mavinic 2002). After stabilization further dewatering of the biosolids usually occurs to form a biosolids cake material. This material is approximately 30% solids and can now be transported for use in land application (GVRD 2002b).

Prior to application of biosolids certain regulations must be considered. In Canada regulations defining biosolids quality are currently being developed with many stemming from the regulations developed by the United States Environmental Protection Agency (USEPA) (Oleszkiewicz and Mavinic 2002). Quality standards in Canada are still evolving and currently each province can set their own limits for biosolids metal levels, application rates and pathogen levels (Epstein 2003).

Biosolids application in BC is regulated under the Organic Matter Recycling Regulation (OMRR) of British Columbia's Waste Management Act. According to this Act biosolids are defined as "stabilized sewage sludge resulting from municipal wastewater treatment which has been sufficiently treated to reduce pathogen densities and vector attraction" (Statutes and Regulations of BC 2004a). This regulation specifies biosolids land application regulations, biosolids quality criteria and soil quality standards for soil treated with biosolids (Statutes and Regulations of BC 2004a). Biosolids can be classified into two classes (A and B) based on their quality (Table 1.1). Class A biosolids meet the criteria outlined in Table 1.2 and also have 99.999% of pathogens destroyed while class B biosolids are slightly higher in metals and have 99.9% of pathogens destroyed (GVRD 2002a).

Biosolids used as an amendment in agriculture are applied at what is termed an agronomic rate. Baseline soil sampling of the site is conducted to determine nutrient availability and the application rate of the biosolids is then based on nutrient application that does not exceed plant requirements (GVRD 2002b). For mine reclamation, biosolids are applied at higher than agronomic rates and are often referred to as a "soil builder" (GVRD 2002b). Application requires baseline soil testing and additional post-application sampling to monitor nutrient levels. After the application of biosolids, soil, water and vegetation samples are collected to ensure that regulatory standards are met. The Contaminated Sites Regulation (Statutes and Regulations of BC 2004b) defines the standards for soil quality and soil samples are compared to concentrations of metals outlined in the OMRR. Water samples are compared to preapplication levels or can be compared to the BC Water Quality Criteria (GVRD 2002b). As there are currently no specific regulations for vegetation quality in BC the dietary tolerances outlined for beef cattle are often used as a guide (GVRD 2002b).

4.2 Biosolids Application to Land

Historically biosolids have been considered a waste product and were disposed of through landfilling, incineration or dumping into the ocean (Bright and Healey 2003). However, with better treatment processes to reduce pathogens and regulations for application levels the use of biosolids as a fertilizer and organic amendment has increased. According to Oleszkiewicz and Mavinic (2002) 63% of biosolids were land applied in the United States in 1998 with the number expected to reach 70% by 2010 with similar trends in Canada. Land application of biosolids is becoming one of the most promising ways to reclaim degraded lands (Sanchez-Monedero et al. 2004) and Palumbo et al. (2004) have even outlined the potential benefits of using waste products such as biosolids in degraded land reclamation as a method for improving C sequestration.

In BC the GVRD is the largest producer of biosolids producing on annual average 90,000 bulk tonnes (Bright and Healey 2003, Duynstee and Lee 2000). Of this, over 70% is used in land application with the remaining material land dried and stored for future recycling use (Duynstee and Lee 2000). In 2002 the GVRD produced 70,687 tonnes of biosolids and supplied 40,348 tonnes for various land application projects (GVRD 2002a). Of the biosolids used for land application the breakdown was 48% for mine reclamation, 47% for native range and pasture land fertilization and the remaining 5% for forestry fertilization, gravel pit reclamation and development of soil products (GVRD 2002a).

4.2.1 Impacts on soil physical properties

In general biosolids application on mine land improves soil physical properties (Sopper 1993) including soil structure, soil water relationships and soil temperature (Epstein 2003) (Table 1.2). The addition of biosolids helps reduce bulk density (Zebarth et al. 1999, Guidi and Hall 1984) which is correlated with an increase in soil porosity (Metzger and Yaron 1987). Pore size distribution is altered by biosolids addition through an increase in macropores (Joost et al. 1987, Pagliai et al. 1983) due to increased aggregate formation in biosolids amended soils (Glauser et al. 1988, Pagliai et al. 1983 from increased soil organic C content causing increased microbial activity (Metzger and Yaron 1987).

The impact of biosolids on soil water relations has been variable among studies. Biosolids increase total water retention of a soil (Zebarth et al. 1999, Joost et al. 1987) but available water holding capacity may be increased (Hinesly et al. 1982) or show no change (Zebarth et al. 1999, Joost et al. 1987). Biosolids have a high water adsorption capacity which results in increased water retention (Gupta et al. 1977) but biosolids also alter soil water relations indirectly by altering bulk density and pore size distribution (Metzger and Yaron 1987). Therefore, changes in soil water holding capacity due to biosolids are impacted by soil texture, amendment water holding capacity and alteration to other soil physical properties.

Soil erosion and runoff are generally decreased by biosolids addition (Kladivko and Nelson 1979) due to increased water infiltration (Younos and Smolen 1983). However, biosolids may also decrease infiltration rates (Gupta et al. 1977). This decrease in infiltration can be offset by the increase in site vegetation which acts to decrease overall soil loss and erosion (Sopper 1993).

4.2.2 Impacts on soil chemical properties

Many studies have examined the impact of biosolids on soil chemical properties, especially with regards to trace elements of concern such as Cd (Table 1.3). For many of the variables the results will be impacted by type of material the biosolids was applied to (e.g. acidic mine spoil, alkaline mine spoil, soil) and chemical makeup of the biosolids. In general biosolids addition helps increase overall soil organic matter content and increases CEC and nutrient availability. Often the most significant increase in macronutrients is with N as it is most often limiting, especially in land disturbed by mining (Topper and Sabey 1986). The advantage of using biosolids as an N source is that most N is in organic form and thus is slowly released for plant use through mineralization (Henry et al. 1991). Phosphorus is also often in limited supply and is readily increased with addition of biosolids. Biosolids often have low levels of K as this element is soluble in sewage sludge and a large portion remains with the effluent (Brady and Weil 1996). The literature is sparse on biosolids addition effects on S levels in the soil but high levels of S containing compounds in biosolids should increase S content.

Micronutrients, often referred to as trace elements, are essential to plants or animals in minute quantities. Biosolids addition usually results in a general increase in micronutrients but the results will vary depending on the content of these elements in the biosolids. In his literature review on using sewage sludge for land reclamation Sopper (1993) concluded most studies found an increase in trace elements with the addition of biosolids. However, the elements tended to decrease with time and their range was usually considered normal and similar to unpolluted and unamended soils (Sopper 1993).

Many of the studies on soil chemistry focused on the impact of biosolids addition on heavy metals. Epstein (2003) defines heavy metals as a group of elements of relatively high molecular weight that can accumulate in specific body organs. However, some trace elements such as Cu, Mo and Zn, are also classified as heavy metals. Since the wastewater collected for biosolids production comes from industrial, commercial and residential sources, levels of heavy metals in biosolids are often elevated (Bright and Healey 2003, Epstein 2003). The concern is that these heavy metals can accumulate in soil and plants and thereby gain entry into the human food chain. High levels of metals may also negatively impact the soil microbial community (Brookes and McGrath 1984) and plant growth (Alloway 1995). For a detailed review of trace elements and heavy metals in soils and plants see Alloway (1995) and Kabata-Pendias and Pendias (1992).

The impact of biosolids on Mo levels has received only a small amount of attention (McBride et al. 2000). Molybdenum is an essential element for plants and animals (Ward 1994, Underwood 1971) and is often not of concern as it is only readily available at higher pH (Edwards et al. 1995). However, on sites with neutral to alkaline pH the increase in Mo from biosolids addition is reflected in the vegetation (Pierzynski and Jacobs 1986). This is cause for concern as high levels of Mo in vegetation can result in a secondary copper deficiency known as molybdenosis in ruminant animals consuming this vegetation (Mills and Davis 1987) which can impact animal health and reproduction and can be life threatening if left untreated. O'Connor et al. (2001) conducted a risk assessment to establish Mo standards for land application of biosolids. Their literature review and data compilation from numerous field studies indicates the risk of molybdenosis from addition of biosolids Mo is small. They also suggest current values in the literature for molybdenosis are low and proper management will further reduce these risks. McBride et al. (2000) suggest Mo should be used as the metal limiting application of biosolids to agricultural land especially if livestock use is considered.

Although not addressed in this study the impacts of dioxins, furans and petroleum hydrocarbons are all areas of concern with biosolids application to land. Bright and Healey (2003) reviewed biosolids produced from five plants in BC. They concluded that with the exception of certain petroleum hydrocarbon substances, following the BC application guidelines for metal and pathogen loading rates when applying biosolids to uncontaminated soils will result in dioxin and furan concentrations remaining below BC soil benchmark standards. Further study on petroleum hydrocarbons is merited (Bright and Healey 2003) and current studies on the impact of dioxins to animal health are underway in BC (Broersma 2004, personal communication).

4.2.3 Impacts on soil microbiological properties

There is little information on the actual microbiological communities present in biosolids but studies on biosolids application to land show an increase in the soil microbial population (Epstein 2003, Albiach et al. 2000, Sastre et al. 1996, Sopper 1993, Seaker and Sopper 1988a, Stroo and Jencks 1982). The addition of biosolids helps increase soil organic matter increasing C and resulting in increased microbiological activity (Seaker and Sopper 1988a). Seaker and Sopper (1988a) studied the population of total aerobic heterotrophic bacteria in coal mine spoil biosolids amended sites from one to five years in age and in a fertilizer amended site. They found the population increase was highest in year one, then decreased but remained higher in biosolids sites than the fertilizer amended site. This initial peak in microbial activity is due to the large amount of easily digestible C sources (sugars, starches, etc.) available directly after biosolids application. Albiach et al. (2000) compared the impact of different organic amendments on microbial biomass and enzymatic activity and found that treatments involving biosolids produced the greatest enhancement of soil enzymatic activity. Sastre et al. (1996) applied biosolids at rates of 50 and 100 Mg ha^{-1} a year for eight years and found biosolids addition increased fungal populations and enzyme activity but the total aerobic bacterial population did not show a clear treatment response. They attributed this to noncomparable nutrient ratios in the different treatment soils and possibly to heavy metal levels but concluded that biosolids application helped increase soil microbiological activity and aid in organic matter decomposition.

The majority of studies focusing on the impact of biosolids on the microbiological community have measured overall microbial activity and total aerobic heterotrophic bacteria (Sopper 1993). Few studies have attempted to differentiate the microbiological community present although some studied enzymatic activities (Albiach et al. 2000, Sastre et al. 1996). Miller (1973 as cited in Epstein 2003) reported that after biosolids application the bacterial population changed from a predominately gram-positive one to a population with over 50% gram-negative bacteria. Seaker and Sopper (1988a) found higher populations of nitrifying bacteria *Nitrosomonas* and *Nitrobacter* on biosolids versus fertilizer amended sites. Little literature exists on the impacts of biosolids on the anaerobic microbiological community.

A concern with biosolids application is that levels of heavy metals in the amendment may inhibit microbiological growth (Moffett et al. 2003). In the above study Seaker and Sopper (1988a) found no negative impacts from biosolids application on the microbiological community and found recovery of the soil microbiological community was aided with biosolids addition over that of fertilizer amended sites. Khan and Chang-yong (1999) also found no negative impacts on microbial activity if biosolids containing low levels of metals were used. Brookes and McGrath (1984), however, found that long-term application of biosolids negatively impacted the soil microbiological community and Sastre et al. (1996) suggested that metal levels in biosolids may be impacting total aerobic bacterial populations. Moffett et al. (2003) found that an agricultural soil with high levels of Zn from biosolids application lowered bacterial diversity versus that of the control soil. Few of these studies addressed the impacts of biosolids addition to sites already containing high metal levels and the resulting effect on the soil microbiological community.

4.2.4 Impacts on vegetation

In reviewing the literature relating to biosolids application one theme is fairly constant; biosolids application helps to increase plant productivity of a site (Norland and Veith 1995, Sopper 1993, Fresquez et al. 1990a and 1990b). This increase is the result of many of the factors outlined in the proceeding sections. Biosolids increase both macro and micronutrients, which are often limiting, especially on lands disturbed by mining activity. Other soil chemical parameters such as organic matter and CEC are also increased with biosolids application. Biosolids addition can help ameliorate soil physical and microbial site limitations by increasing factors such as water availability. In a study conducted by Norland and Veith (1995) on alkaline iron ore tailings, the addition of composted biosolids helped increase vegetation cover from 0 to over 70% in a four year period, with some treatments resulting in greater than 90% cover.

Biosolids addition can also alter species composition of a site. Fresquez et al. (1990b) noted a decrease in plant diversity, species richness and total plant density when biosolids were applied to degraded semiarid grassland in New Mexico. However, they did note an overall increase in yield and total cover of plants considered desirable to the site and the decrease of others considered weedy. Pierce et al. (1998) studied biosolids application to a sagebrush community in Western Colorado. They noted an increase in biomass; perennial grasses and forbs, mid-seral shrubs, and mountain big sagebrush remained the dominant species, with annual species never accounting for more than 3% total canopy cover. In mine reclamation, the site is often devoid of vegetation and depending on provincial requirements and site limitations, agronomic grass and legume forage species are used for reclamation.

Biosolids addition increased both soil nutrients and heavy metals (Sanchez-Monedero et al. 2004, McBride 2003, Sopper 1993). A concern is that some of these elements may be accumulated in the vegetation at higher than normal rates, impacting plant growth and animal health. An increase in soil element levels is not always directly reflected in the vegetation. Factors such as pH, soil nutrient holding capacity, soil organic matter, soil texture and soil temperature and level and form of elements present in the biosolids applied all impact potential bioavailability of elements to the vegetation (McBride 2003, Harrison et al. 1991). Studies on the impact of biosolids application on nutrient uptake in plants grown on amended sites show a general increase in major plant nutrients such as N, P, K, Ca and Mg (Sopper 1993). However, in literature reviews

McBride (2003) and Sopper (1993) also noted increases in heavy metals such as Cu, Zn, chromium (Cr), Pb, Cd and nickel (Ni) following biosolids addition. McBride (2003) summarized information from various studies and ranked metals based on their soil-plant barrier from strongest to weakest as follows: Pb, Cr, mercury (Hg)>Cu>Ni, Zn, Cd>Mo. This means metals such as Zn, Cd and Mo are fairly accessible to plant uptake which is of concern as Cd and Zn accumulate in animal organs (Fitzgerald 1982) and Mo can result in molybdenosis in ruminant animals (Mills and Davis 1987).

4.2.5 Impacts on domestic livestock and wildlife

Biosolids can impact wildlife and domestic livestock through soil ingestion or through consumption of vegetation or feed grown on biosolids amended sites via pathogens, trace elements such as heavy metals and toxic compounds (Epstein 2003). Biosolids can also impact wildlife through changes to the composition and structure of plant communities, which can then alter habitat for wildlife in the area (Neuman et al. 1991). Biosolids can introduce trace metals into the environment which can be ingested by wildlife. Anderson et al. (1982 as cited in Neuman et al. 1991) studied metal uptake in meadow voles living in areas treated with biosolids and found Cd concentration in livers and kidneys increased over controls but metal accumulation was below the toxic threshold. Biosolids can impact mesofauna. Pietz et al. (1984 as cited in Neuman et al. 1991) applied biosolids to mine spoil and studied metal concentrations in earthworms, finding metal concentration generally increased in biosolids amended sites. Forge et al. (2003) found apple orchards treated with biosolids or municipal compost had a higher abundance of protozoa and nematodes and the nematode community showed species enrichment versus that of an unamended control. However, very limited literature exists on the impact of biosolids on large ungulates.

More studies have been conducted on domestic animals but research results are still limited (Epstein 2003). A primary concern is that higher metal levels in forage may result in metal accumulation in animals and potential entry into the human food chain. Research on effects of sludge application on domestic animals does not show clear trends on accumulation although in general the accumulation of trace metals occurs mainly in the liver and kidney (Neuman et al. 1991). The main metal of concern is Cd due to its availability and toxicity (Epstein 2003, Neuman et al. 1991). Baxter et al. (1982 as cited in Neuman et al. 1991) conducted a study of grazing beef cattle on a biosolids amended site. They slaughtered a subsample of these animals and compared metal levels in kidney, liver, bone, muscle and fat tissues to animals grazing a nonamended site. They found higher levels of Cd and Zn in kidney and higher Pb in bone tissue than control cattle but all stayed within the normal range for cattle of that age. Few reports exist on pathogen contamination of domestic animals from biosolids application (Epstein 2003). Fitzgerald (1979, 1982) studied cattle grazing on land treated with biosolids and found no disease or transmission of pathogens from the biosolids. He noted increases in Cd and Pb in the kidney and liver but levels remained below that considered harmful for human consumption.

Molybdenum is another heavy metal that may be of concern in reclamation of alkaline areas with biosolids. High levels of Mo in vegetation can result in molybdenosis for ruminant animals consuming this forage. The National Research Council (1980) stated that Mo concentrations greater than 10 ppm in forage may result in diarrhea, emaciation and death. O'Connor et al. (2001) concluded the risk of molybdenosis from biosolids Mo is small. On mined areas with a high concentration of Mo in the waste material the risk may be elevated since Mo levels in the spoil are already high. A study at Highland Valley Copper mine grazed cattle on mine tailings reclaimed with inorganic fertilizer amendments and found the average forage Mo levels were 34 ppm over a three year period but cattle showed no signs of molybdenosis and liver Cu levels remained normal (Gardner et al. 2003).

4.3 Biosolids versus Other Amendments

Other organic amendments such as animal manures, wood waste, pulpmill sludge, crop residues and peat can be used as organic amendments. Zebarth et al. (1999) compared different organic amendments applied to a sandy, infertile soil in the southern interior of BC. They applied biosolids from different areas in BC, a composted poultry manure and food waste product, composted hog manure solids and peat at a rate of 45

$Mg\ ha^{-1}$ for a four year period and found bulk density decreased, soil organic matter and soil water retention increased and limited changes were noted for cation exchange capacity and soil water holding capacity. There was little difference in soil chemical and physical properties among the different amendments.

When compared among sites applied with manure and biosolids, the latter have a higher plant nutrient content (Land Resource Network Ltd. 1993). Animal manures supply both macro and micronutrients but typically at lower amounts than biosolids (Land Resource Network Ltd. 1993). Thus there is less of a concern with heavy metal loading on sites treated with animal manures than those amended with biosolids. As noted above, both amendments have similar impacts on soil physical properties and act to stimulate soil biological activity (Land Resource Network Ltd. 1993). Wood waste is more variable in quality but in general has higher levels of C than N and very limited amounts of micronutrients (Land Resource Network Ltd. 1993).

A major consideration in applying organic amendments to land disturbed by mining is availability and cost of the amendment. In BC, use of biosolids in mine reclamation is very attractive since the GVRD currently has a recycling program that covers cost of shipping and application of the material to selected mine sites. This incentive makes the application of biosolids much more cost effective than animal manure or wood waste products.

Another amendment typically used in mine reclamation is inorganic fertilizer. The majority of studies comparing inorganic fertilizer to biosolids found biosolids are much more effective at ameliorating poor site conditions and developing a more stable plant community (Seaker and Sopper 1988a, Stroo and Jencks 1982). This is because inorganic fertilizer additions only deal with nutrient deficiency limitations and do not directly alter soil physical characteristics. Nutrients applied in an inorganic form are readily dissolved in water and available for plant uptake when applied, which can lead to nutrient loss through leaching and runoff. For fertilization to be effective as a mine reclamation tool it appears a management program with yearly repeated applications must be put into place until the plant community has developed to a point where it can deal with some of the other site limitations such as low organic matter and poor water retention.

5. GAPS IN THE CURRENT RESEARCH

Past research on biosolids and inorganic fertilizer application has addressed many soil physical and chemical impacts of biosolids and their effect on plant growth, but few have integrated all these components and assessed the system as a whole. Most studies on the impact of biosolids application on soil microbial populations have researched total aerobic heterotrophs and have not further defined the microbial community.

The majority of the research using biosolids as a reclamation tool has been conducted on coal mine spoils and acidic sites. Limited studies have been carried out on alkaline mine tailings, especially those high in Mo and Cu. Comparison of treatment response on mine tailings of different texture is limited. Reclamation and revegetation of tailings with high Mo and Cu levels present unique challenges. The effect of biosolids addition on animal health has been studied but the impact of biosolids on Mo levels in the vegetation and possible molybdenosis risks in relation to high Mo tailings reclamation have not been addressed.

6. RESEARCH OBJECTIVES

The main objective of this research was to determine the impacts of biosolids and inorganic fertilizer amendments on soil physical, chemical and microbial properties, and vegetation yield, composition and element uptake within and/or over a three year period in Cu and Mo mine tailings. Comparison of a sandy site and a silt loam site were conducted to observe whether treatment response varied by texture. A further objective was to discuss the interrelationships of the above properties within the context of the soil-plant-water-animal system. Consideration was given to the reclamation challenges and health concerns in the above system and to the economic and biological efficiency of the reclamation practices. The research hypothesis was that biosolids amendments would help to speed soil development and ecosystem function versus use of inorganic fertilizer amendments or no amendments.

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Table 1.1. Biosolids quality criteria (adapted from GVRD 2002a and Statutes and Regulations of BC 2004a)

Substance (ppm dry weight unless otherwise noted)	Class A Biosolids	Class B Biosolids	Biosolids Used at the Sand and Silt Loam Tailings
Arsenic	75	75	7.5 to 10
Cadmium	20	20	5.5 to 6
Chromium	1060	1060	64 to 71
Cobalt	150	150	4 to 5.5
Copper	2200	2200	967 to 969
Lead	500	500	105 to 110
Mercury	5	15	4.2*
Molybdenum	20	20	10 to 10.5
Nickel	180	180	25
Selenium	14	14	4.6*
Zinc	1850	1850	959 to 983
Fecal Coliform MPN** g^{-1}	<1000	<2,000,000	Not analyzed

*Average values from GVRD analysis

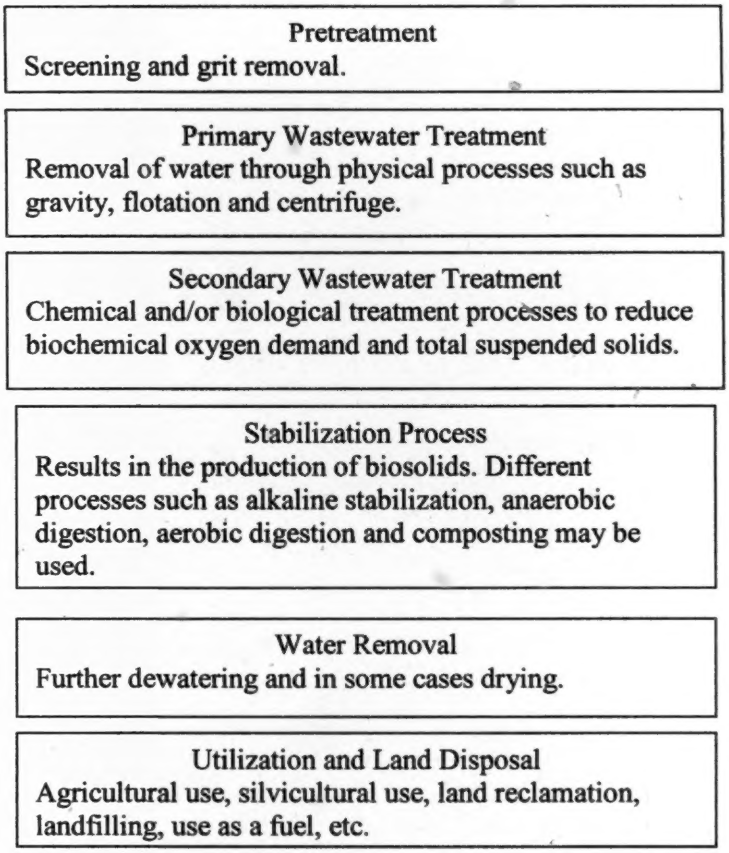
** MPN – most probable number

Table 1.2. Summary of the literature and effects of biosolids on soil physical properties.

Parameter	Result	Reference
Soil Structure		
Bulk density	Reduction	Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Gupta et al. 1977
Altered pore size distribution	Increase in macropores	Joost et al. 1987, Pagliai et al. 1983
Aggregate formation	Increase	Glauser et al. 1988, Joost et al. 1987, Hinesly et al. 1982, Epstein 1975
Soil Water Relations		
Water retention	Increase	Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Metzger and Yaron 1987, Hinesly et al. 1982, Gupta et al. 1977, Epstein et al. 1976, Epstein 1975
Water holding capacity	Increase	Hinesly et al. 1982
	No change	Zebarth et al. 1999, Joost et al. 1987, Epstein 1975
Water infiltration	Increase	Cocke and Brown 1987, Younos and Smolen 1983
	Decrease	Gupta et al. 1977
Soil Erosion/Runoff	Decrease	Kladivko and Nelson 1979
Soil Temperature	Decrease	Hornick 1982

Table 1.3. Summary of the literature and effects of biosolids on soil chemical properties.

Parameter	Result	Reference
pH	Variable	Zebarth et al. 1999, Brown et al. 1997, Tester 1990, Topper and Sabey 1986
Electrical conductivity	Increase	Tsadilas et al. 1995, Topper and Sabey 1986, Guidi and Hall 1984, Hinesly et al. 1982
Cation exchange capacity	Increase	Sopper 1993, Guidi and Hall 1984
Soil organic matter and soil carbon	Increase	Walter et al. 2002, Tester 1990, Glauser et al. 1988, Seaker and Sopper 1988b, Visser et al. 1983, Varanaka et al. 1976
Macronutrients		
Nitrogen	Increase	Franco-Hernandez et al. 2003, Sopper 1993, Hinesly et al. 1982, Griebel et al. 1979, Epstein et al. 1976
Phosphorus	Increase	Tsadilas et al. 1995, Topper and Sabey 1986, Hinesly et al. 1982, Epstein et al. 1976
	No change	Franco-Hernandez et al. 2003, Griebel et al. 1979, Mathias et al. 1979
Potassium	Little impact	Sopper 1993
	Decrease	Hinesly et al. 1982
	Increase	Fresquez et al. 1990a and 1990b
Calcium	Variable	Sopper 1993
	Increase	Mathias et al. 1979, Epstein et al. 1976
Magnesium	Increase	Mathias et al. 1979
Sulfur	n/a	Not documented
Micronutrients		
B, Co, Cu, Fe, Mn, Mo, Zn	Varies with element but generally increases	Walter et al. 2002, Sopper 1993, Tsadilas et al. 1995, Fresquez et al. 1990a and 1990b, Hinsely et al. 1982, Griebel et al. 1979
Other elements		
As, Cd, Cr, Ni, Pb	Varies with element but generally increases	Sanchez-Monedero et al. 2004, Berti and Jacobs 1996, Sopper 1993, Hinsely et al. 1982, Griebel et al. 1979, Peterson et al. 1979



Pretreatment

Screening and grit removal.

Primary Wastewater Treatment

Removal of water through physical processes such as gravity, flotation and centrifuge.

Secondary Wastewater Treatment

Chemical and/or biological treatment processes to reduce biochemical oxygen demand and total suspended solids.

Stabilization Process

Results in the production of biosolids. Different processes such as alkaline stabilization, anaerobic digestion, aerobic digestion and composting may be used.

Water Removal

Further dewatering and in some cases drying.

Utilization and Land Disposal

Agricultural use, silvicultural use, land reclamation, landfilling, use as a fuel, etc.

Figure 1.1. Typical wastewater treatment process (adapted from Epstein 2003 and Oleszkiewicz and Mavinic 2002).

II. INFLUENCE OF BIOSOLIDS AND FERTILIZER AMENDMENTS ON SELECTED SOIL PHYSICAL, CHEMICAL AND MICROBIOLOGICAL PROPERTIES IN TAILINGS REVEGETATION

ABSTRACT

A three-year field study was conducted at the Highland Valley Copper mine, on a silt loam and a sandy site, to determine effects of fertilizer and biosolids amendments on selected soil physical, chemical and microbial properties. Following increasing biosolids addition at dry rates of 50, 100, 150, 200 and 250 Mg ha^{-1}, soil bulk density decreased linearly and penetration resistance decreased with increasing biosolids for the upper 6 to 12 cm of tailings, remaining below 3 MPa for both sites. Biosolids addition increased gravimetric water content at field capacity and wilting point but no significant changes occurred in water holding capacity. On a volumetric basis, water holding capacity decreased with increasing amounts of biosolids for the silt loam site, but showed no change for the sandy site. Soil pH was not impacted by the treatments where as electrical conductivity, soil organic matter, total carbon and cation exchange capacity increased with increasing levels of biosolids. Biosolids addition increased total aerobes, total anaerobes, iron reducers, sulfate reducers and denitrifiers in the soil surface horizon, while the fertilizer amendment did not alter soil physical or chemical parameters from that of the control.

1. INTRODUCTION

In Canada, over 0.4 million ha of land have been disturbed by mining activities (Natural Resources Canada 2002). In British Columbia (BC) the open pit mining of molybdenum (Mo) and copper (Cu) results in the generation of tailings when the ore is extracted and large areas referred to as tailings ponds are created where the spent ore is deposited. The tailings, because of their adverse physical and chemical properties and lack of a microbial population are often difficult to revegetate (Norland and Veith 1995, Munshower 1994). Traditional revegetation efforts have mostly involved addition of chemical fertilizer but have little effect in speeding soil development in the creation of a stable, self-sustaining site (Seaker and Sopper 1988b, Topper and Sabey 1986, Tate 1985, Stroo and Jencks 1982). Organic amendments have been useful in improving soil properties on disturbed areas (Land Resources Network Ltd. 1993). An amendment that has gained popularity is stabalized sewage sludge, commonly referred to as biosolids. The addition of biosolids to disturbed sites has increased vegetation biomass and cover and helped promote soil formation allowing more rapid establishment of a self-sustaining site (Seaker and Sopper 1988b).

Most studies on biosolids have been related to soil nutrient parameters and metal movement and only a small percentage have addressed the impact of biosolids on soil physical properties (Land Resources Network Ltd. 1993, Metzger and Yaron 1987). In general, biosolids applications on disturbed mine land have improved the physical properties of spoil materials as a growth medium for establishment and growth of vegetation (Sopper 1993). The addition of biosolids generally leads to an increase in soil organic matter and total soil carbon (C) (Tester 1990, Glauser et al. 1988, Seaker and Sopper 1988b, Visser et al. 1983, Varanka et al. 1976), which can lead to an increase in soil water retention (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Metzger and Yaron 1987, Hinesly et al. 1982, Gupta et al. 1977, Epstein et al. 1976, Epstein 1975). However, the addition of biosolids has had conflicting results when calculated as soil water holding capacity, increasing it in some cases (Hinesly et al. 1982) and resulting in no changes in others (Zebarth et al. 1999, Joost et al. 1987, Epstein 1975). Soil texture can also impact how biosolids influence water holding capacity with the organic amendment having more of an impact on sandy soils (Metzger and Yaron 1987).

The effectiveness of biosolids on water holding capacity is mainly related to water holding capacity of the amendment itself (Metzger and Yaron 1987) but alterations in soil structure due to biosolids application also impact water storage. Biosolids addition cause a reduction in bulk density, directly increasing porosity (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Gupta et al. 1977). Martens and Frankenberger (1992) and Joost et al. (1987) demonstrated that biosolids amendment lead to an increase in soil C, which increased aggregate formation and favourably altered soil structure. Other studies showed the addition of biosolids increased aggregate stability (Glauser et al. 1988, Hinesly et al. 1982, Epstein 1975) and altered pore size distribution, increasing the percentage of macropores (Pagliai et al. 1983). However, Agassi et al. (1998) noted that biosolids amendments decreased the final percolation rate as they can clog soil pores.

Biosolids additions have altered soil pH (Zebarth et al. 1999, Brown et al. 1997, Tester 1990, Joost et al. 1987, Topper and Sabey 1986, Guidi and Hall 1984, Hinesly et al. 1982, Griebel et al. 1979, Peterson et al. 1979, Epstein et al. 1976), increased electrical conductivity (EC) (Tsadilas et al. 1995, Topper and Sabey 1986, Guidi and Hall 1984, Hinesly et al. 1982, Epstein et al. 1976) and increased cation exchange capacity (CEC) (Guidi and Hall 1984). The increase in CEC can have a direct impact on nutrient retention and therefore on plant growth. The addition of large amounts of metals to a site is particularly a concern as mine tailings often already are high in specific metals.

Biosolids addition leads to increased organic matter of the material receiving the biosolids (Sastre et al. 1996, Seaker and Sopper 1988b, Visser et al. 1983, Varanka et al. 1976) which increases C availability for microbial utilization thus directly augmenting soil microbiological activity (Sastre et al. 1996 and Seaker and Sopper 1988a). Most studies assessing the impact of biosolids on soil microorganisms focused on aerobic heterotrophic bacteria, soil respiration and enzymatic activity (Albiach et al. 2000, Sastre et al. 1996, Sopper 1993, Seaker and Sopper 1988a, Stroo and Jencks 1982). Seaker and Sopper (1988a) found a significant increase in the aerobic heterotrophic bacteria population for biosolids amended mine sites over those receiving chemical fertilizers. Sastre et al. (1996) found no clear treatment response for total aerobic bacteria populations with differing levels of biosolids versus a control and fertilizer treatment but found increased fungal populations, enzymatic activity and overall microbiological activity for the biosolids amended sites. However, only a limited number of studies have been conducted to address the role of other microbiological groups in response to biosolids addition.

Khan and Chang-yong (1999) and Seaker and Sopper (1988a) stated that microbial populations in biosolids amended sites did not impact microbiological activity if low-metal biosolids are used (Khan and Chang-yong 1999). Brookes and McGrath (1984) noted adverse effects on the soil microbial community with long-term addition of biosolids due to increased metal levels. Moffett et al. (2003) found high zinc (Zn) levels in an agricultural soil treated with biosolids reduced bacterial diversity compared to an untreated control. Few studies addressed the impact of biosolids metal additions on sites already containing high metal levels and the resulting affect on the soil microbiological community.

Although there has been an increase in studies investigating soil processes such as heavy metal movement, limited research has been conducted linking soil physical, chemical, microbiological and vegetation responses of biosolids amendments at different or increasing application rates and comparing these responses to a fertilizer amendment. The objective of this research is to assess changes in soil physical, chemical and microbiological parameters due to increasing rates of biosolids and inorganic fertilizer amendments on two different tailing materials of sandy and silt loam texture over a three year period.

2. MATERIALS AND METHODS

2.1 Study Site Description

This research was conducted at the open pit Highland Valley Copper (HVC) mine located approximately 80 km southwest of Kamloops and 210 km northeast of Vancouver, BC, Canada. The mine is located in the Thompson Plateau physiographical subdivision, in an open-ended valley between glacially eroded mountains and glacial overburden covers most of the land as glacial till (Broersma 1997). Highland Valley is a low-grade (0.4%) porphyry copper-molybdenum deposit located in the central part of the late Upper Triassic Guichon Creek batholith (Casseleman et al. 1995). The batholith is a composite, calc-alkaline and I-type intrusion put in place about 210 million years ago (Casseleman et al. 1995). The district has five major porphyry Cu-Mo deposits: Valley, Lornex, Bethlehem, Highmont and JA (Casseleman et al. 1995).

Two different tailings sites on the HVC mine were studied. Prior to disturbance the soils consisted of predominately Gray Luvisols. However, due to the site disturbance the tailings on the site are now considered unclassified. Trojan tailings are located at 1400 m above sea level and are of sandy texture (hereinafter referred to as sand tailings).

This pond was milled from Valley pit granodiorite rocks containing 60% plagioclase, 10% K-feldspar, 10% quartz, 8% biotite and minor amounts of other elements including calcite and gypsum. Bethlehem tailings are 1450 m above sea level and are texturally classified as a silt loam (hereinafter referred to as silt loam tailings). This pond was milled from Bethlehem pit granodiorite rocks, containing approximately 60% plagioclase, 10% K-feldspar, 10% quartz, 8% hornblende and minor amounts of other elements including calcite. Both tailings are alkaline with pH 7 to 8.

The general area has a continental climate characterized by warm, dry summers and cool winters; however, more extreme temperatures exist at this site because of the higher elevations. The main factor controlling climate is the rainshadow created in the lee of the Coastal Mountains due to the prevailing easterly flowing air (Hope et al. 1991). Growing season moisture deficits are common and frosts can occur at any time (Hope et al. 1991). Climate normals from the Lornex weather station between 1967 and 1990 indicate that 1998 was a drier than normal year and temperatures were above normal resulting in drought conditions (Table 2.1). The conditions in 1999 were also drier than normal but cooler weather resulted in more effective precipitation during the growing season. The 2000 conditions were wetter than average (69% above normal) while temperatures remained close to normal.

Upon closure of the mine an estimated total of 6,900 ha of land will be disturbed with 2,700 ha of tailings ponds (Freberg and Gould Gizikoff 1999). The primary end land use goal for the tailings sites is cattle and wildlife grazing or forage production (Appendix A).

2.2 Experimental Design and Treatments

Two study sites were established in summer 1998. At each site a randomized complete block design with seven treatments and eight blocks was constructed. Blocks were to deal with a moisture gradient due to locations near the tailing ponds. Each plot was 3 by 7 m with a buffer strip of 1 m between blocks. Treatments consisted of a control (C0), a fertilizer amendment (F0) and biosolids applied at dry rates of 50, 100, 150, 200 and 250 Mg ha^{-1} (B50, B100, B150, B200 and B250, respectively).

Anaerobically digested sewage sludge (biosolids) from the Greater Vancouver Regional District (GVRD) was stockpiled at each site and samples were randomly collected from each stockpile to determine chemical composition (Table 2.2). Dry weight per volume of biosolids was determined prior to application. Biosolids were applied by volume using an all terrain vehicle (ATV), shovel and rake. Biosolids were left to dry for a 2 week period to ease incorporation by a tractor mounted rototiller into the tailings to a depth of approximately 15 cm. In June 1999, the site was broadcast seeded with a grass legume mix and lightly raked by hand. Species were pubescent wheatgrass (*Agropyron trichophorum* (Link) Richt.), orchard grass (*Dactylis glomerata* L.), creeping red fescue (*Festuca rubra* L. var. *rubra*), Russian wild ryegrass (*Elymus junceus* Fisch.), alfalfa (*Medicago sativa* L.), and alsike clover (*Trifolium hybridum* L.) seeded at rates to produce 20, 20, 15, 15, 15 and 15% cover of each species, respectively. At the time of seeding the inorganic fertilizer was manually broadcast on the fertilizer plots but was not incorporated. The fertilizer contained nitrogen (N), phosphorus (P), potassium (K), Zn, and boron (B) and was formulated to be similar in these nutrients to the biosolids 150 Mg ha^{-1} treatment based on biosolids and soil analysis data from the fall 1998 sampling.

In 1998, prior to application of biosolids, baseline soil sampling was completed at both sites to test for homogeneity. Soil sampling occurred in mid to late September in 1998, 1999 and 2000 using a random grid and destructive sampling locations were never located in the same area twice.

2.3 Soil Physical Properties

Silt and clay content were determined by the hydrometer method after removing the sand fraction by sieve (McKeague 1978) and results were used to classify soil texture for each site. Bulk density was determined in 1999 and 2000 using the core method (Blake and Hartage 1986) and one 75 mm diameter core was collected per plot for the 0 to 15 cm depth increment. In September 1998, soil penetration resistance was measured to 60 cm at 1.5 cm intervals (Bradford 1986) using a hand pushed 13 mm diameter cone (30^{o}) penetrometer with attached data logger (Agridry Rimik PTY Ltd., Toowoomba, QLD, Australia). Five data log profiles were recorded per plot. Time domain reflectometry (TDR) Moisture Point Model 917 and PRB-H profiling probes were used in selected plots due to a limited number of probes (fertilizer, biosolids 100 Mg ha^{-1} and biosolids 200 Mg ha^{-1} treatments on 4 blocks per site) in 1998 to determine soil moisture to a 60 cm depth at 15 cm increments (Topp 1993). Gravimetric soil moisture was calculated for the top 0 to 15 cm depth in selected plots (control, biosolids 50 Mg ha^{-1}, biosolids 150 Mg ha^{-1} and biosolids 250 Mg ha^{-1} treatments on 2 blocks per site) in 1998 using the oven dry method (Topp 1993). Sampling was conducted on selected treatments only in order to represent the range of treatments applied to the sites. Water holding capacity (WHC) was determined only in 1998 for the upper 0 to 15 cm depth for all treatments and blocks using the pressure plate method (McKeague 1978). Intact cores were not used and samples analyzed had been ground to pass through a 2 mm sieve. Pressures of 0.01, 0.033, 0.2 and 1.5 MPa were used to determine moisture retention curves for each treatment and a total of eight replicates per treatment were used. Water holding capacity was determined by subtracting field capacity from wilting point (1.5 MPa). For the sandy site, 0.01 MPa was used for field capacity (Webster and Beckett 1972) and for the silt loam, 0.033 MPa was used (Jamison and Kroth 1958). Volumetric data were calculated by multiplying gravimetric data and the 1999 bulk density for each plot.

2.4 Soil Chemical Properties

Soil core collection for chemical analysis was conducted manually with a hydraulic core sampler (2.7 cm inside diameter) taking five 50 cm cores and splitting the samples into depth intervals of 0 to 15, 15 to 30 and 30 to 45 cm. The five individual depth increments were placed in one bag to form a composite sample for each plot at each depth. Samples were air dried to a constant weight (approximately one week) and passed through a 2 mm sieve on a hammer mill prior to chemical analyses. Chemical analyses were conducted on samples from all years, all treatments and all depths, except for soil organic matter, which was only analyzed in 1998, due to financial constraints, using the upper 0 to 15 cm.

Soil pH was measured using 0.01 M $CaCl_2$ but samples were left to equilibrate for one week prior to reading to obtain a stable reading (Hendershot et al. 1993a). Salinity was determined as electrical conductivity (Janzen 1993). Percent total C was determined by dry combustion with the Carlo-Erba instrument (Nelson and Sommers 1996) and soil organic matter content was determined by ashing samples in a muffle furnace at 600 °C for 6 hours (Ball 1964). Total CEC and exchangeable cations (Na^+, Mg^{+2}, K^+, Ca^{+2}) were determined using the ammonium acetate method at pH 7.0 (Hendershot et al. 1993b).

2.5 Soil Microbiological Properties

Soil for microbial analyses was taken from 0 to 10 cm and maintained in an anaerobic environment at 4 °C until analysis took place. Sampling was only conducted on biosolids treatments 50, 150, 250 Mg ha^{-1}, control and fertilizer treatments due to the costs. Samples were analyzed for total heterotrophic aerobes in 1998 and 2000. In 2000 samples were also analyzed for most probable number (MPN) of total anaerobes, iron reducers, sulfate reducers and denitrifiers (Carter 1993). A standard plate count technique using serial dilutions plated on Difco plate count agar was used for determining total heterotrophic aerobes (Carter 1993).

2.6 Data Analyses and Interpretation

Analysis of variance (ANOVA) conducted on baseline samples showed homogeneity within sites for the majority of the variables but significant differences between sites for all variables tested (Steel et al. 1997). Residuals were tested for normality using the Shapiro-Wilk test (Schlotzhauer and Littell 1997). Many of the data were not normally distributed, and transformations were made, with no effect on statistical conclusions. To further study the distribution, data were examined graphically using g tests and tested for homogeneity of variance using Bartlett's test (Steel et al. 1997). Soil physical and chemical data that were not normally distributed met the assumption of equality of variances and therefore parametric tests were conducted on the original (untransformed) data. Most soil microbiological data did not meet the assumption of normality or equality of variance and were therefore examined statistically using a nonparametric test.

For soil physical and chemical parameter data a two way analysis of variance was conducted on each site for each year and each depth. If treatment effect was significant the following planned orthogonal contrasts and polynomials were conducted: 1) Do increasing rates of biosolids show a linear effect, 2) Do increasing rates of biosolids show a quadratic effect, 3) Is the control treatment different from the inorganic fertilizer treatment, and 4) Is the inorganic fertilizer treatment different from the biosolids 150 Mg ha^{-1} treatment? Year effects were studied by using a split-plot design with treatment as the main plot and year as the subplot. As baseline sampling confirmed that sites were significantly different for the majority of variables, a nested split-plot design with treatment as the main plot, year as the subplot and block nested within location was used to determine if a treatment by location interaction was occurring. All statistical analyses were conducted using the Proc Mixed with random command in SAS (SAS Institute, version 8). Analyses on the three depths were conducted separately and statistical comparisons were not made among depths. For soil microbiological data a nonparametric Freidmans 2- way ANOVA was conducted (Siegel and Castellan 1988).

Data that were statistically different but showed no biological significance were not reported (for statistical design/program used and complete tables refer to Appendices B and C). Results were considered significant at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Soil Physical Properties

3.1.1 Texture, bulk density and penetration resistance

The texture of the Trojan tailings was sand (92.8 % sand, 5.7 % silt, 1.6 % clay) and Bethlehem was silt loam (19.6 % sand, 66.9 % silt, 13.6 % clay). Bulk density in the 0 to 15 cm depth in 1999 and 2000 showed a significant linear decrease with increasing levels of biosolids (Tables 2.2 and 2.3) which supports other findings (Zebarth et al.

1999, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Gupta et al. 1977). Bulk densities at the silt loam and sand sites ranged from 1.25 to 0.67 and 1.47 to 0.90 Mg m^{-3}, respectively, falling within or below normal range (Brady 1990), and thus not limiting plant growth. The decrease in bulk density with biosolids amendment can be directly related to increased porosity which can lead to improved soil aggregation (Guidi and Hall 1984).

Penetration resistance increases with increasing bulk density and decreasing soil moisture (Bennie 1991). At the silt loam site penetration resistance remained below 2 MPa for the 60 cm depth measured where as at the sand site it was > 2 but < 3 MPa from 24 to 60 cm (Appendix C). According to a rating system for threshold values related to plant growth (Naeth et al. 1991) values ≤ 2 MPa are good and values >2.0 but ≤ 3.0 are fair. Hence, at both sites soil resistance was not limiting root growth. Increasing amounts of biosolids resulted in a significant decrease in penetration resistance for the silt loam 0 to 6 cm depth (p=0.0001) and in the sand 0 to 6 cm (p=0.0016) and 6 to 12 cm (p=0.0084) depths. These results support those of Tester (1990) who found biosolids additions significantly reduced penetration resistance on sandy loam soils.

3.1.2 Soil moisture and water holding capacity

Field soil moisture generally showed no treatment effect. The exception was in the upper 0 to 15 cm in 1998 at the sand site where soil moisture significantly increased with increasing amounts of biosolids. Epstein et al. (1976) noted an increase in soil moisture with biosolids > 160 Mg ha^{-1}. The data from this study, although not statistically significant, does indicate increasing moisture content with increased biosolids (silt loam site control at 13.8% moisture vs biosolids 250 Mg ha^{-1} treatment at 24.6% and sand site control at 0.6% moisture vs 250 Mg ha^{-1} treatment at 16.3%).

Increasing biosolids significantly increased gravimetric soil moisture in all cases except for 0.2 MPa at the silt loam site (Table 2.3) which supports results in the literature (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Metzger and Yaron 1987, Hinesly et al. 1982, Gupta et al. 1977, Epstein et al. 1976, Epstein 1975). Graphing on a volumetric basis resulted in the entire water retention curve at the sand site shifting toward higher water contents but available water holding capacity (AWHC) did not significantly change (Figure 2.1). These results were similar to those from Gupta et al. (1977) for a sandy soil where the majority of the increase in water retention due to the sludge resulted from water remaining in the soil even at high pressures (1.5 MPa) so the curve shifted upwards while overall AWHC remained unchanged.

Sludge addition impacts on AWHC are still controversial (Metzger and Yaron 1987). Previous researchers found either an increase (Hinesly et al. 1982) or no associated change (Zebarth et al. 1999, Joost et al. 1987, Gupta et al. 1977, Epstein 1975). This study supports those findings at the sandy site but not at the silt loam site. At the silt loam site AWHC significantly decreased with increasing biosolids addition when calculated on a volumetric basis (Table 2.3). The linear decrease in water retention with higher biosolids at the lower pressures (0.01 and 0.033 MPa) and subsequent increase at higher pressures (1.5 MPa) (Table 2.3) can be explained by the impact of organic amendments on soil structure. Addition of biosolids decreased bulk density, increasing soil porosity; but many studies have demonstrated that sludge addition can also increase aggregate stability (Martens and Frankenberger 1992, Glauser et al. 1988, Joost et al. 1987, Hinesly et al. 1982, Epstein 1975) and alter pore size distribution (Joost et al. 1987, Pagliai et al. 1983). At higher suction values, such as wilting point (1.5 MPa), the increase in water retention is influenced more by texture and specific surface of the soil material (Hillel 1982), thus at both sites is related directly to the increase in overall surface area caused by organic matter addition (Gupta et al. 1977). At lower pressures, pore size will have more impact on water retention (Hillel 1982). In a sandy soil the pores are relatively large while in a silt loam there will be more micropores (Hillel 1982). Therefore, at the silt loam site the addition of biosolids may have increased aggregation thus increasing pore size over that of the control.

3.2 Soil Chemical Properties

3.2.1 pH

Soil pH was not impacted by treatment and average values over the three years ranged from 7.3 to 7.5 for the silt loam site and 7.0 to 7.3 for the sand site (Appendix C), generally within the acceptable range for crop plants (Brady 1990). As the pH of biosolids is generally close to neutral, addition of biosolids typically decreases pH at alkaline sites (Zebarth et al. 1999, Topper and Sabey 1986, Hinesly et al. 1982, Peterson et al. 1979, Epstein et al. 1976) and increases it at acidic sites (Brown et al. 1997, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Griebel et al. 1979). In this study biosolids pH was slightly lower than the unamended tailings. Both Brown et al. (1997) and Tester (1990) noted a greater pH increase at depth on coarse textured soils although our results show no significant treatment by site interactions.

3.2.2 Electrical conductivity

For the 0 to 15 cm depth interval increasing rates of biosolids resulted in a significant increase in EC at both sites (Table 2.4). A similar increase was also noted by Tsadilas et al. (1995), Topper and Sabey (1986), Hinesly et al. (1982), Epstein et al. (1976) and in a review paper by Guidi and Hall (1984). In 1998, at the biosolids 250 Mg ha^{-1} treatment level, EC at the silt loam site exceeded the recommended maximum of 4 dS m^{-1} (Brady 1990). Both Topper and Sabey (1986) and Hinesly et al. (1982) both found ECs of >4 dS m^{-1} decreased grass growth but application rates increasing EC were > 224 Mg ha^{-1} in Hinesly et al. (1982) vs the much lower rates of 83 Mg ha^{-1} for Topper and Sabey (1986). In 1999 EC dropped below 4 dS m^{-1} and a significant decrease was noted in all three years at both sites (Appendix C).

Our results are similar to those of Epstein et al. (1976) who found higher ECs in the first year with a subsequent reduction with time. At depths of 15 to 30 and 30 to 45 cm a significant increase in EC was still noted on both sites in most years but all ECs remained below 1 dS m^{-1}.

3.2.3 Soil carbon and organic matter

Soil total C for 0 to 15 cm significantly increased with increasing biosolids rates (Table 2.5). As C at both sites was initially low, the majority of the C likely came from the biosolid amendment that is largely organic.

Soil organic matter increased with biosolids addition (Table 2.6). The organic matter of unamended tailings was significantly different with site. Silt loam values were representative of the range of soil organic matter found in the upper 15 cm of a typical mineral soil that is 1 to 4% (Brady 1990), where as sand values were slightly lower. Soil total C significantly decreased after the first year. Seaker and Sopper (1988b), Visser et al. (1983) and Varanka et al. (1976) all noted spoil organic matter increased with sludge addition and site age. Seaker and Sopper (1988b) attributed this to an increase in microbial processes and vegetation cover. However, Tester (1990) found decreased organic C over a four and a half year study and attributed it to increased organic matter decomposition. The slight decrease in total C in the first two years of our study can be attributed to increased decomposition as indicated by the initial increased soil microorganisms. Vegetation was established in spring 1999 and the resulting increase in litter accumulation and decomposition was likely not evident in the short study time. Increased total biomass production on the biosolid amended sites will likely continue to add organic matter resulting in an increase or stabilization of organic matter over time. At depths of 15 to 30 and 30 to 45 cm a treatment effect was not predominant and total soil C ranged from 0.55 to 1.01% at the silt loam site and 0.29 to 0.47% at the sand site (Appendix C).

3.2.4 Cation exchange capacity

The CEC at the silt loam site was much higher than at the sand site (Table 2.7). This was expected since coarse textured soils, such as sands, have lower CEC because they have lower amounts of colloids and thus overall surface area to sorb cations (Brady 1990). The control treatment at the silt loam site in 1998 had an average CEC of 2.1 cmol (+) kg^{-1}, lower than the 13 to 26 cmol (+) kg^{-1} typically found in silt loam soils. The control treatment at the sand site in 1998 had an average CEC of 0.13 cmol (+) kg^{-1}, also lower than the 2 to 3 cmol (+) kg^{-1} typical of sandy soils (Brady 1990). As tailings are ground parent material and contain little or no organic matter (Table 2.6) these low CEC values are expected.

At both sites, biosolids addition led to a significant increase in CEC at a depth of 0 to 15 cm (Table 2.7) which can be directly related to the increase in soil organic matter. These findings are consistent with many other studies that also found an increase in organic matter content and therefore an increase in CEC with biosolids (Guidi and Hall 1984). This increase in CEC is positive for soil nutrient retention. In contrast to these results, Zebarth et al. (1999) found no increase in CEC when biosolids were applied at 45 Mg ha^{-1} to a loamy sand soil in southern interior BC even though a substantial increase was predicted. They concluded that immediate beneficial increases in soil CEC do not automatically follow organic amendments addition. At depths of 15 to 30 and 30 to 45 cm treatment had little impact on total CEC and values ranged from 1.25 to 6.63 cmol (+) kg^{-1} at the silt loam site and <0.01 to 2.50 cmol (+) kg^{-1} at the sand site (Appendix C). As the amendment was only incorporated into the top 15 cm of the tailings overall treatment effect on CEC is confined to that depth.

The base saturation was dominated by Ca^{+2}, with K^+, Na^+ and Mg^{+2} accounting for the remainder (Appendix C). The high levels of Ca^{+2} are due to the composition of the material ground to form the tailings. This rock contains 60% plagioclase which contains calcium but is not calcareous. The host rock also contains very small amounts of calcite. The summing of total exchangeable cations results in a total greater than the total CEC using the laboratory method. High levels of cations present in the soil solution may not be bound on the cation exchange sites as excess cations can dry on the soil surface and become part of the exchangeable cations when extracted (Sumner and Miller 1996). High levels of Ca^{+2} may also have competed with the NH_4^+ (ammonium) in the extraction procedure resulting in a lower determined CEC than the material actually has (Hendershot et al. 1993b).

3.3 Soil Microbiological Properties

On unamended mine tailings, low soil organic matter and plant growth result in low number of aerobic heterotrophic bacteria (Seaker and Sopper 1988a) as these bacteria require soil organic matter as their energy source (Sastre et al. 1996, Killham 1994). For the control and inorganic fertilizer treatments at both sites in 1998 total aerobic heterotrophs were well below the range of 1 to 34 x 10^6 g^{-1} in undisturbed soils (Sopper 1993) (Table 2.8). Addition of biosolids resulted in a steady increase with increasing biosolids (Table 2.8). In 2000, treatment effect was only significant at the sand site, however, at both sites total aerobes at each biosolids level dropped. This slight reduction can be explained by a higher level of microbial activity with initial organic matter application due to more readily available C followed by a reduction in activity as microorganisms were exposed to more resistant and harder to decompose components of organic matter (Sopper 1993). As well, the dry site conditions may have contributed to the microbial population decline.

Total anaerobes at each site showed a significant treatment effect (Table 2.8). Addition of high amounts of organic matter can increase anaerobic conditions due to a general increase in total soil microbial activity and therefore higher use of oxygen (Bremner 1977). Iron reducers, sulfate reducers and denitrifiers all showed significant treatment effects (Table 2.8). Biosolids addition increased these organisms vs the control while fertilizer addition had varying effects (Table 2.8). Sulfate reducers are heterotrophic obligate anaerobes that use sulfate (SO_4^{-2}) as their terminal electron acceptor and soil organic matter as their energy source (Killham 1994). A review by Bremner (1977) stated additions of soil amendments led to increased sulfur (S) volatilization which is supported by our results as sulfate reducers are responsible for S volatilization. Denitrifiers are heterotrophic facultative anaerobes that use nitrate (NO_3^-) as their terminal electron acceptor and soil organic matter as their energy source (Killham 1994). Supplying additional organic matter can increase denitrification due to an increase in oxidizable substrate for the bacteria and to a general decrease in soil oxygen due to decomposition of soil organic matter (Bremner 1977). The increase in the denitrifier population may also be related to the fact that these organisms are also involved in aerobic decomposition.

The impact of metal levels on the microbial community was not evaluated for in this study but increases in all bacteria studied indicate the effect was not negative. Khan and Chang-yong (1999) reviewed the literature on heavy metal pollution effects on soil microbial biomass and found biosolids with low metal content have little impact while high metal levels biosolids negatively impact microbial biomass. The metal levels of Cu and Mo at our sites were higher due to their residual levels in the unamended tailings.

In general, the addition of biosolids increased overall microbial community numbers vs the unamended control which is beneficial as it increases soil organic matter decomposition and nutrient cycling, which are important in site recovery to produce a sustainable ecosystem (Seaker and Sopper 1988a and 1988b, Segal and Mancinelli 1987).

3.4 Fertilizer versus Biosolids Amendment

For all variables investigated in this study, there were no significant differences between the fertilizer treatment and control. Most significant treatment effects resulted in a significant contrasting difference between the fertilizer and biosolids 150 Mg ha^{-1} treatments. These findings confirm those of Seaker and Sopper (1988a, 1988b) who compared a sludge amendment (120 to 134 Mg ha^{-1}) to a one time fertilizer application and noted little change in soil organic matter, organic C, N, overall plant growth and microbial numbers for the fertilizer treatment. Studies show fertilizer amendment on reclaimed areas may initially increase plant growth but productivity decreases after the fertilizer is discontinued indicating that fertilizer amendment has little impact on soil formation and site stabilization (Seaker and Sopper 1988, Topper and Sabey 1986, Tate 1985, Stroo and Jencks 1982).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

- At these study sites a one time incorporation of biosolids at five different rates had beneficial impacts on most soil physical, chemical and microbiological properties studied.
- Tailings texture impacted almost all parameters studied thus playing an important role in determining response to biosolids amendment.

- The benefits of biosolids amendment continued over the three years of the study as evidenced by increased CEC levels.
- Most of the treatment response occurred in the zone of biosolids incorporation, the upper 0 to 15 cm of tailings.
- Fertilizer had no significant impact on any of the parameters studied.

4.2 Management Recommendations

- On fine textured or highly saline sites, waiting a year between biosolid incorporation at high rates of biosolids application ($\geq$ 150 Mg ha^{-1}) and seeding or applying biosolids in the fall and seeding the next spring may be useful as EC levels are highest directly after biosolids application.
- If cost or amount avaialbale is a factor, biosolids application at rates as low as 50 Mg ha^{-1} can help ameliorate some site limitations to plant growth for the parameters investigated in this study. However, as treatment response was linear for most parameters, higher levels of biosolids (up to 250 Mg ha^{-1}) would be most beneficial.
- On moisture limited sand tailings sites, other amendments (e.g. clay) may be required to help increase plant available water while on finer textured tailings sites with higher moisture levels biosolids addition may increase aeration.
- Organic amendments such as biosolids are more effective at promoting soil development and therefore more effective for reclamation of tailing sites than the use of inorganic fertilizer.

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Table 2.1. Climate information at the tailings sites over the three years from the Lornex weather station (C.E. Jones and Associates 1999, 2000 and 2001).

Variable	1998	1999	2000
Snowfall from November 1 to March 31 (cm)	88	157	77
Rainfall from November 1 to March 31 (mm)	77	59	25
Precipitation from April to October (mm)	182	172	386
Temperature range from April to October (°C)	-6.5 to 33	-11 to 28	-8.5 to 28
Growing degree days	1509	975	1037
Frost free period (days)	173	136	169
Monthly mean annual minimum temperature (°C)	-5 (Jan)	-5 (Dec)	-5 (Dec)
Monthly mean annual maximum temperature (°C)	17.5 (Aug)	15 (Aug)	15 (July)

Table 2.2. Mean values of selected chemical analyses of biosolid stockpiles at the sand and silt loam tailings.

Variable	Silt Loam Site Biosolids	Sand Site Biosolids
pH	6.3	6.8
Electrical conductivity (dS m^{-1})	8.1	7.5
Total carbon (%)	29.1	31.1
Dry matter (%)	24.5	23.8

Table 2.3. Bulk density, gravimetric and volumetric water holding capacity at the silt loam and sand sites for 0 to 15 cm.

Site and Treatment	Bulk Density	Gravimetric Water Holding Capacity ($g\ g^{-1}$ x 100)					Volumetric Water Holding Capacity ($cm^3\ cm^{-3}$ x 100)				
	$Mg\ m^{-3}$	0.01 MPa	0.033 MPa	0.2 MPa	1.5 MPa	WHC (%)	0.01 MPa	0.033 MPa	0.2 MPa	1.5 MPa	WHC (%)
Silt Loam											
Control	1.31[1]	50.3	39.4	18.6	4.8	34.6	65.9	51.6	24.4	6.3	45.3
	0.03[2]	6.7	11.0	10.8	1.6	9.4	8.9	13.8	13.5	2.0	11.9
Fertilizer	*1.30	*50.3	39.2	*21.2	*4.8	34.4	*65.4	*51.0	27.6	*6.2	*44.7
	0.03	6.5	11.7	12.6	1.5	10.2	8.3	14.7	15.9	1.9	12.8
Biosolids 50	1.10	51.0	36.6	18.6	5.8	30.8	56.1	40.3	20.5	6.4	33.9
	0.11	8.2	14.5	12.8	1.9	12.7	13.9	19.7	16.4	2.6	17.3
Biosolids 100	1.10	56.5	43.4	20.0	8.1	35.3	62.2	47.7	22.0	8.9	38.8
	0.07	7.1	12.1	9.3	2.2	10.1	5.7	11.4	9.4	2.2	9.6
Biosolids 150	*0.90	*59.5	44.0	*21.4	*11.8	32.2	*53.6	*39.6	19.3	*10.6	*29.0
	0.10	6.2	12.2	7.8	1.3	12.0	10.0	13.8	8.8	1.9	12.7
Biosolids 200	0.90	58.7	44.4	21.5	14.0	30.4	52.8	40.0	19.4	12.6	27.4
	0.09	8.8	14.2	8.9	3.9	12.8	9.4	13.1	8.3	4.0	11.2
Biosolids 250	0.70	63.6	48.4	25.6	17.8	30.6	44.5	33.9	17.9	12.5	21.4
	0.14	6.6	11.6	5.5	4.8	13.4	8.1	9.3	3.8	3.4	10.1
p value	0.0001 linear	0.0001 linear	0.0006 linear	0.0555	0.0001 linear	0.2364	0.0001 linear	0.0019 linear	0.2281	0.0001 linear	0.0001 linear

[1] Mean for N = 8 for each site

[2] Standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

WHC = (0.033 MPa water – 1.5 MPa water)

Table 2.3. Bulk density, gravimetric and volumetric water holding capacity at the silt loam and sand sites for 0 to 15 cm (continued).

Site and Treatment	Bulk Density	Gravimetric Water Holding Capacity (g g^{-1} x 100)					Volumetric Water Holding Capacity (cm^3 cm^{-3} x 100)				
	Mg m^{-3}	0.01 MPa	0.033 MPa	0.2 MPa	1.5 MPa	WHC (%)	0.01 MPa	0.033 MPa	0.2 MPa	1.5 MPa	WHC (%)
Sand											
Control	1.50	7.3	5.0	2.3	1.0	6.3	11.0	7.5	3.5	1.5	9.5
	0.04	1.3	1.6	1.1	0.1	1.3	1.9	2.4	1.6	0.2	1.9
Fertilizer	*1.50	*7.9	*4.7	*3.0	*1.0	6.9	*11.9	*7.1	*4.5	*1.5	10.4
	0.03	2.9	1.4	2.2	0.2	2.9	4.3	2.0	3.1	0.2	4.2
Biosolids 50	1.40	9.3	6.3	3.8	2.5	6.8	13.0	8.8	5.3	3.5	9.5
	0.05	3.1	2.2	1.3	0.6	2.8	4.1	2.9	1.5	0.8	3.8
Biosolids 100	1.30	10.6	7.4	5.2	4.2	6.4	13.8	9.6	6.8	5.5	8.3
	0.12	2.6	1.8	1.4	1.5	2.3	3.5	2.7	1.8	2.0	3.3
Biosolids 150	*1.10	*14.4	*10.2	*8.1	*6.7	7.7	*15.8	*11.2	*8.9	*7.4	8.5
	0.07	2.6	1.4	2.1	1.1	2.1	3.5	2.0	2.9	1.6	2.5
Biosolids 200	1.00	17.5	15.0	11.5	9.4	8.1	17.5	15.0	11.5	9.4	8.1
	0.19	4.2	6.8	2.6	2.7	2.2	4.8	8.5	2.1	2.7	2.6
Biosolids 250	0.90	23.8	17.4	15.2	13.6	10.2	21.4	15.7	13.7	12.2	9.2
	0.23	6.9	4.6	4.7	4.0	4.6	9.7	6.4	6.6	6.1	5.3
p value	0.0001 linear	0.0001 linear	0.0001 linear	0.0001 linear	0.0001 quadratic	0.0922	0.0004 linear	0.0005 linear	0.0001 linear	0.0001 linear	0.8959

[1] Mean for N = 8 for each site

[2] Standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

WHC = (0.01 MPa water – 1.5 MPa water)

Table 2.4. Soil electrical conductivity (dS m^{-1}) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	1.63	0.27	1.40	0.64	1.30	0.37
Fertilizer	*1.55	0.53	*1.16	0.63	*1.35	0.60
Biosolids 50	2.07	0.84	1.60	0.65	1.53	0.69
Biosolids 100	2.60	0.64	2.19	0.81	1.81	0.48
Biosolids 150	*3.77	0.33	*2.38	0.78	*2.19	0.67
Biosolids 200	3.98	0.40	2.44	0.38	1.89	0.35
Biosolids 250	4.68	0.60	2.89	0.51	2.21	0.62
p value	0.0001 linear		0.0001 linear		0.0001 linear	
Sand Site						
Control	0.06	0.01	0.05	0.01	0.05	0.01
Fertilizer	*0.06	0.01	*0.06	0.02	*0.04	0.01
Biosolids 50	0.46	0.17	0.22	0.07	0.08	0.03
Biosolids 100	0.84	0.34	0.41	0.23	0.14	0.09
Biosolids 150	*1.63	0.34	*0.58	0.17	*0.22	0.13
Biosolids 200	2.08	0.54	0.84	0.35	0.33	0.11
Biosolids 250	2.78	0.36	1.44	0.64	0.58	0.28
p value	0.0001 linear		0.0001 quadratic		0.0001 quadratic	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

Table 2.5. Soil total carbon (%) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	0.68	0.14	0.60	0.04	0.73	0.22
Fertilizer	*0.62	0.09	*0.54	0.06	*0.79	0.15
Biosolids 50	1.81	0.70	1.20	0.88	2.06	0.91
Biosolids 100	2.68	0.84	1.73	1.04	2.95	1.22
Biosolids 150	*4.67	0.77	*2.04	1.72	*3.73	1.16
Biosolids 200	5.25	0.68	2.32	1.49	4.46	1.00
Biosolids 250	6.96	1.56	3.34	2.32	4.47	0.74
p value	0.0001 linear		0.0002 linear		0.0001 quadratic	
Sand Site						
Control	0.30	0.02	0.29	0.03	0.27	0.03
Fertilizer	*0.30	0.02	*0.29	0.02	*0.29	0.04
Biosolids 50	1.17	0.32	0.77	0.23	0.81	0.46
Biosolids 100	1.61	0.58	1.47	0.59	1.24	0.34
Biosolids 150	*2.52	0.46	*1.74	0.52	*1.97	0.77
Biosolids 200	3.83	1.06	2.28	0.88	2.38	0.44
Biosolids 250	5.81	1.72	3.44	1.14	2.94	0.69
p value	0.0001 quadratic		0.0001 linear		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

Table 2.6. Soil organic matter (%) means for 0 to 15 cm for 1998.

Treatment	Silt Loam Site 1998	SD	Sand Site 1998	SD
Control	2.5	0.6	0.7	0.1
Fertilizer	*2.6	0.4	*0.8	0.1
Biosolids 50	6.2	2.5	2.2	0.9
Biosolids 100	7.2	3.6	3.1	2.3
Biosolids 150	*15.7	6.2	*6.8	2.5
Biosolids 200	15.6	5.8	11.4	5.5
Biosolids 250	22.2	8.2	15.8	8.7
p value	0.0001 linear		0.0001 quadratic	

N = 8 for each site

SD = Standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

Table 2.7. Cation exchange capacity (cmol (+) kg^{-1}) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	2.13	0.83	2.88	0.83	6.50	7.56
Fertilizer	* 2.13	0.83	*2.63	0.92	*4.38	1.41
Biosolids 50	4.00	1.41	4.63	0.74	7.63	2.26
Biosolids 100	5.25	1.67	5.00	1.41	7.13	2.03
Biosolids 150	*8.13	0.99	*7.00	2.56	*7.00	5.37
Biosolids 200	9.00	1.60	7.88	2.53	13.38	5.85
Biosolids 250	12.13	1.96	11.25	2.49	16.13	4.12
p value	0.0001 linear		0.0001 linear		0.0001 linear	
Sand Site						
Control	0.13	0.35	0.88	0.35	0.88	0.35
Fertilizer	*0.63	0.74	*0.75	0.46	*0.83	0.21
Biosolids 50	2.00	0.76	1.63	0.74	2.88	1.64
Biosolids 100	2.38	0.92	2.75	1.28	3.50	2.39
Biosolids 150	*5.75	3.24	*2.88	1.73	*5.38	2.39
Biosolids 200	4.75	2.92	3.88	2.10	7.00	1.85
Biosolids 250	8.13	1.89	7.25	3.81	8.75	2.49
p value	0.0001 linear		0.0001 quadratic		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference for orthogonal contrast control vs fertilizer treatment

Table 2.8. Soil aerobes and anaerobes at the silt loam and sand sites in the upper 10 cm of tailings.

Treatment	Total Aerobes (10^5 g^{-1})				Total Anaerobes (10^4 g^{-1})		Iron Reducers (10^2 g^{-1})		Sulfate Reducers (10^2 g^{-1})		Denitrifiers (10^3 g^{-1})	
	1998	SD	2000	SD		SD		SD		SD		SD
Silt Loam												
Control	2.2	2.4	640	1090	4.2	5.1	4.3	6.8	1.4	3.0	3.8	8.2
Fertilizer	1.5	0.9	790	1520	13.5	22.7	2.4	1.7	0.2	0.3	22.1	47.9
Biosolids 50	23635.0	36288.3	840	1480	45.2	70.0	47.5	91.0	3.4	3.5	120.4	168.1
Biosolids 150	30337.5	29525.0	500	790	118.9	75.3	447.1	1130.5	10.3	10.1	282.5	368.9
Biosolids 250	38400.0	47028.4	420	630	389.6	826.9	607.1	1078.0	33.4	33.1	456.4	416.8
p value	0.0001		0.0754		0.0001		0.0001		0.0001		0.0001	
Sand												
Control	8.1	14.7	97.0	270.0	1.0	1.0	4.9	8.6	3.0	7.6	3.4	8.4
Fertilizer	1.5	1.5	1.4	0.8	1.9	1.5	1.9	0.9	0.4	0.4	5.5	8.2
Biosolids 50	5946.3	5412.1	290.8	585.6	53.8	73.4	167.8	187.3	4.0	3.4	46.5	79.9
Biosolids 150	7212.5	3957.8	223.1	285.7	79.3	85.8	155.9	88.7	5.0	5.1	110.2	111.8
Biosolids 250	9062.5	4667.2	416.2	540.5	146.4	84.7	255.3	100.3	19.8	43.1	440.7	545.2
p value	0.0001		0.0001		0.0001		0.0001		0.0028		0.0001	

N = 8 for each site and each year
SD = Standard deviation

III. INFLUENCE OF BIOSOLIDS AND FERTILIZER AMENEDMENTS ON ELEMENTAL CONCENTRATIONS IN REVEGETATED TAILINGS

ABSTRACT

A three-year field study was conducted on two mine tailings sites consisting of silt loam and sand textures at the Highland Valley Copper mine in British Columbia to determine the effects of fertilizer and biosolids amendments on soil elemental concentration. Following biosolids additions at dry matter rates of 50, 100, 150, 200 and 250 Mg ha^{-1}, the soil concentration increased for total N, C, P, S, Mg, Fe, Zn, Ni and Pb and available NO_3-N, NH_4-N, P, Fe, Mn and Zn at both sites. No change was noted for total K, B, Co, Cu, Mn, As, Cd, Cr or available Cu. Total Ca increased with treatment at the sand site only. Total Mo decreased at the sand site and available Mo decreased at the silt loam site. Soil element concentrations were not highly impacted by time, and treatment response was mainly confined to the upper 15 cm of the soil. The fertilizer amendment did not alter soil elemental concentrations for the added nutrients from that of the control.

1. INTRODUCTION

In Canada, over 0.4 million ha of land are disturbed by mining activities (Natural Resources Canada 2002). By law, this disturbed land in the Province of British Columbia (BC) must be reclaimed to a self-sustaining state (Regional Operations, Health and Safety Branch 1997). Reclamation challenges vary with type of mining activity and the physical and chemical properties of the material to be reclaimed. In BC, open pit mining and the resulting production of tailings ponds is common for many copper (Cu) and molybdenum (Mo) mines. Some of the major challenges of reclaiming tailings from hard rock mineral mining are that these materials are often nutrient poor, may contain heavy metals that are toxic to plants, lack organic matter and normal microbial populations, are subject to erosion, have low water holding capacity and lack soil structure (Norland and Veith 1995). Revegetation of these sites will help to reduce erosion and increase organic matter content but is difficult given the site conditions. Addition of inorganic fertilizers alone appears to be inefficient and requires a high level of annual management to establish a self-sustaining plant community (Seaker and Sopper 1988). Biosolids addition as an organic amendment has helped ameliorate many of these problems (Epstein 2003, Norland and Veith 1995, Sopper 1993, Seaker and Sopper 1988). Biosolids addition, however, can increase concentrations of some elements to levels of environmental concern (McBride 2003). This is especially true if the end land use plan for these areas involves use by domestic animals or wildlife and there is the potential of these elements to enter into the human food chain.

Much of the biosolids research has focused on the impact of biosolid additions to soils and mine spoil material and the resulting changes in element concentration in the soil profile. In general, studies have documented that the addition of biosolids increases the soil macronutrients nitrogen (N) and phosphorus (P), has a variable effect on calcium (Ca), magnesium (Mg) and sulfur (S) and has little impact on potassium (K) (Sopper 1993). Biosolids additions also tend to increase trace elements and metals such as cadmium (Cd), chromium (Cr), Cu, iron (Fe), nickel (Ni), lead (Pb) and zinc (Zn) (Sanchez-Monedero et al. 2004, Walter et al. 2002, Seaker 1991, Hinesly et al. 1982, Griebel et al. 1979).

Regulations re biosolids application to agricultural land and disturbed lands in British Columbia are determined by the concentration of total metals in the material (Statutes and Regulations of BC 2004) although the fact that element toxicity is related more to availability than total concentrations is accepted (Sanchez-Monedero et al. 2004). Therefore it is important to study extractable elemental concentrations, metals that exist in exchangable, organically complexed and carbonate forms, as these give more information on the metal bioavailability and correlate with plant uptake of these metals (Walter et al. 2002).

The majority of studies on mine site reclamation with biosolids are focused on coal mine spoils in the United States (Sopper 1993, Seaker 1991, Seaker and Sopper 1988, Topper and Sabey 1986, Joost et al. 1987, Hinesly et al. 1982, Griebel et al. 1979, Peterson et al. 1979). These sites are often acidic and thus metal availability is impacted to a greater degree. Limited research has been conducted on alkaline mine tailings from Cu and Mo mining and the impact that biosolid additions have on nutrient and metal concentrations and movements in the soil. Although a large portion of the research on biosolid applications has focused on the impact of metal addition to soils it is important to have an understanding of metal behaviour in each specific situation as metal behaviour in soils and plant uptake can vary with differing biosolids materials, site soil properties and plants grown on the site (McBride 2003). Most studies have focused on a single textural class of material and have not compared how biosolids treatment may be impacted by sites with similar climate and elevation but different soil textures. This research evaluates the impact of biosolids and fertilizer amendments on the elemental composition of sand and silt tailings.

2. MATERIALS AND METHODS

2.1 Study Site Description

The research was conducted at the open pit Highland Valley Copper (HVC) mine located approximately 80 km southwest of Kamloops and 210 km northeast of Vancouver BC, Canada. The mine is located in the Thompson Plateau physiographical subdivision, in an open-ended valley between glacially eroded mountains and glacial overburden covers most of the land as glacial till (Broersma 1997). Highland Valley is a low-grade (0.4%) porphyry copper-molybdenum deposit located in the central part of the late Upper Triassic Guichon Creek batholith (Casseleman et al. 1995). This batholith is a composite, calc-alkaline and I-type intrusion put in place about 210 million years ago (Casseleman et al. 1995). The district has five major porphyry Cu-Mo deposits: Valley, Lornex, Bethlehem, Highmont and JA (Casseleman et al. 1995).

Two different tailings sites on the HVC mine were studied. Prior to disturbance the soils consisted of predominately Gray Luvisols. However, due to site disturbance, the tailings on the site are now considered unclassified. Trojan tailings are located 1400 m above sea level and are texturally classified as a sand (hereinafter referred to as sand tailings). This pond was milled from Valley pit granodiorite rocks containing 60% plagioclase, 10% K-feldspar, 10% quartz, 8% biotite and minor amounts of other elements including calcite and gypsum. Bethlehem tailings are 1450 m above sea level and are texturally classified as a silt loam (hereinafter referred to as silt loam tailings). This pond was milled from Bethlehem pit granodiorite rocks, containing approximately 60% plagioclase, 10% K-feldspar, 10% quartz, 8% hornblende and minor amounts of other elements including calcite. Both tailing sites are alkaline with a pH of 7 to 8.

The area has a continental climate characterized by warm, dry summers and cool winters; however, more extreme temperatures exist at this site because of the higher elevations. The main factor controlling climate is the rainshadow created in the lee of the Coast Mountains due to the prevailing easterly flowing air (Hope et al. 1991). Substantial growing season moisture deficits are common and frosts can occur at any time (Hope et al. 1991). Climate normals from the Lornex weather station between 1967 and 1990 indicate that 1998 was a drier than normal year and temperatures were above normal resulting in drought conditions (Table 3.1). The conditions in 1999 were also drier than normal but cooler weather resulted in more effective precipitation during the growing season. The 2000 conditions were wetter than average (69% above normal) while temperatures remained close to normal.

Upon closure of the mine an estimated total of 6,900 ha of land will be disturbed with 2,700 ha of tailings ponds (Freberg and Gould Gizikoff 1999). The primary end land use goal for the tailings sites is cattle and wildlife grazing or forage production (Appendix A).

2.2 Experimental Design and Treatments

The two study sites were established in the summer of 1998. At each site a randomized complete block design with seven treatments and eight blocks was constructed. Blocks were to deal with a moisture gradient. Each plot was 3 by 7 m and a buffer strip of 1 m was placed between blocks. Treatments consisted of a control (C0), a fertilizer amendment (F0), and dry biosolids at rates of 50, 100, 150, 200 and 250 Mg ha^{-1} (B50, B100, B150, B200, and B250 respectively).

Anaerobically digested sewage sludge (biosolids) from the Greater Vancouver Regional District (GVRD) was stockpiled at each site and samples were collected from each stockpile to determine chemical composition (Table 3.2). Dry weight per volume of biosolids was determined prior to application. Biosolids were applied by volume using an all terrain vehicle (ATV), shovel and rake. Biosolids were left to dry for a 2 week period to ease incorporation by a tractor mounted rototiller into the tailings to a depth of approximately 15 cm. In June 1999 the site was broadcast seeded with a grass legume mix and lightly raked by hand. Species were pubescent wheatgrass (*Agropyron trichophorum* (Link) Richt.), orchard grass (*Dactylis glomerata* L.), creeping red fescue (*Festuca rubra* L. var. *rubra*), Russian wild ryegrass (*Elymus junceus* Fisch.), alfalfa (*Medicago sativa* L.), and alsike clover (*Trifolium hybridum* L.) and seeded at rates to produce 20, 20, 15, 15, 15 and 15% cover of each species, respectively. At the time of seeding the inorganic fertilizer was manually broadcast on the fertilizer plots but was not incorporated. The fertilizer contained N, P, K, Zn, and boron (B) and was formulated to be similar in these nutrients to the biosolids 150 Mg ha^{-1} treatment based on biosolids and soil analysis data from the fall 1998 sampling (Table 3.3).

In 1998, prior to application of biosolids, baseline soil sampling was completed at both sites to test for homogeneity. Soil sampling occurred in mid to late September in 1998, 1999 and 2000 using a random grid and destructive sampling locations were never located in the same area twice.

2.3 Soil Chemical Properties

Soil core collection for chemical analysis was conducted manually with a hydraulic core (2.7 cm inside diameter) sampler taking five samples per plot at 0 to 15, 15 to 30, and 30 to 45 cm depths. The five cores were then placed in one bag to form a composite sample for each plot at each depth. Samples were air dried to a constant weight (approximately one week) and passed through a hammer mill with a 2 mm sieve prior to chemical analyses. Chemical analyses were conducted on samples from all years, all treatments and all depths, except for nitrate-N (NO_3-N), ammonium-N (NH_4-N) and total S which due to costs were only analyzed using the top 0 to 15 cm.

Laboratory analyses on the composite soil samples were conducted for total arsenic (As), B, Ca, Cd, cobalt (Co), Cr, Cu, Fe, K, Mg, manganese (Mn), Mo, Ni, P, Pb, and Zn using a strong acid digestion with HNO_3 (Huang et al. 2004, Hewitt and Reynolds

1990). Extracts from the strong acid digestion were analyzed using a Thermo Jarrell Ash 61E simultaneous inductively coupled argon plasma atomic emission spectrophotometer (ICP). Total S was determined by extracting 0.5 grams of dried sieved soil with bromine water, HNO_3 and HCl and then run using a Perkin Elmer P40 sequential inductively coupled argon plasma atomic emission spectrophotometer with nitrogen purged optics. Total carbon (C) and total N were analyzed by dry combustion with the Carlo-Erba instrument (Nelson and Sommers 1996). Available Cu, Fe, K, Mn, Mo, P and Zn were determined using the ammonium bicarbonate-diethylenetriamine pentaacetic acid (AB-DTPA) extraction and read with the ICP (Sims and Eivazi 1997). Available nitrogen (NO_3-N and NH_4-N) where analyzed by extraction with 1.0M KCl (Maynard and Kalra 1993) and determined with a Technicon Analyzer II (Technicon Industrial System 1977 and 1978).

2.4 Data Analyses and Interpretation

Analysis of variance (ANOVA) conducted on baseline samples showed homogeneity within sites for the majority of the variables but significant differences between sites for all variables tested (Steel et al. 1997). Residuals were tested for normality using the Shapiro-Wilk test (Schlotzhauer and Littell 1997) and raw data were tested for homogeneity of variance using Bartlett's test (Steel et al. 1997).

A two way analysis of variance was conducted on each site at each year and each depth. When the treatment effect was significant the following pre-planned orthogonal contrasts and polynomials were conducted: 1) Do increasing rates of biosolids show a linear effect, 2) Do increasing rates of biosolids show a quadratic effect, 3) Is the control treatment different from the inorganic fertilizer treatment, and 4) Is the inorganic fertilizer treatment different from the biosolids 150 Mg ha^{-1} treatment? Year effects were studied by using a split-plot design with treatment as the main plot and year as the subplot. As baseline sampling confirmed that the sites were significantly different with respect to the majority of the variables, a nested split-plot design with treatment as the main plot, year as the sub plot and block nested within location was used to determine if a treatment by location interaction was occurring. All statistical analyses were conducted using the Proc Mixed with random command in SAS (SAS Institute, version 8). Analyses on the three depths were conducted separately and statistical comparisons were not made among depths.

Data that were significantly different but showed no biological significance were not reported (for statistical design/program used and complete tables refer to Appendices B and D). Results were considered to be significant at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Macronutrients

3.1.1 Total and available nitrogen

At both sites, a significant linear treatment response occurred with increasing amounts of biosolids (Table 3.4). The control and fertilizer treatments were not significantly different but the 150 Mg ha^{-1} biosolids treatment differed from the inorganic fertilizer treatment. Mean total N control values of the silt loam site averaged 0.016% over three years while that of the sand site was 0.004%, indicating both sites were deficient in N compared to normal soils (Table 3.5). The increased total N with increasing biosolids addition was also noted by Franco-Hernandez et al. (2003), Sopper (1993), Hinesly et al. (1982), Griebel et al. (1979) and Epstein et al. (1976).

Total C increased in response to biosolids addition in the upper 0 to 15 cm (Table 2.6; Chapter II). Biosolids addition lowered the C:N ratio while it remained high in the control and fertilizer treatments mainly due to very low N (Table 3.4). In general, a C:N ratio of <20:1 will lead to net mineralization while a ratio of >30:1 will lead to net immobilization (Tisdale et al. 1985). Franco-Hernandez et al. (2003) also noted increased C mineralization with addition of different bisolids. This increase in net mineralization is related to the increase in activity and numbers of heterotrophic microorganisms (Table 2.9) and may lead to increased N loss via leaching of more mobile inorganic N forms such as NO_3-N.

Both forms of inorganic N increased in response to increasing levels of biosolids (Tables 3.7 and 3.8). At the sand site in 1998, NH_4-N had a high mean with large variability for the biosolids 200 Mg ha^{-1} treatment resulting in a non-significant treatment effect. This value may be due to sampling error. Topper and Sabey (1986) stated the deficiency level for a dryland grass pasture was approximately 6 ppm available NO_3-N. They also noted increasing levels of NO_3-N with increased biosolids ranging from 0.8 ppm in their control to 53 ppm in the biosolids 83 Mg ha^{-1} treatment. Franco-Hernandez et al. (2003) found biosolids increased NH_4-N but NO_3-N was not different from the unamended control. They speculated that NH_3 volatilization due to high pH may partially explain the lack of increase in NO_3-N. Epstein et al. (1976) found NO_3-N and NH_4-N levels changed depending on when in the season they sampled. Values were higher in early and late fall when plants were no longer actively growing and taking up inorganic N. Epstein et al. (1976) also reported NH_4-N levels were higher in biosolids vs composted treatments indicating more rapid mineralization. This mineralization will increase plant available NH_4-N unless it is in excess of plant needs in which case it can be oxidized to NH_3-N, immobilized, adsorbed by clays or volatilized (Brady and Weil 1996). Large quantities of NO_3-N are associated with higher leaching potential and high rates of biosolid additions do not necessarily result in increased N uptake by plants (Barbarick et al. 1996). Therefore, while increasing total N is beneficial to tailing sites, the higher NO_3-N from higher biosolids may increase N loss via leaching. On sites with pH above 7 there is an increased potential for volatilization of ammonia and subsequent loss from the soil (Henry et al. 1991).

There was a significant year effect for total N with highest values in 1998, dropping slightly for biosolids amended treatments in 1999 and 2000 (Table 3.4). These findings are consistent with those of Seaker and Sopper (1988) who found total N remained constant on one to five year old sites, indicating much of the N in the system is conserved and losses due to NO_3-N leaching or ammonia volatilization were small. NO_3-N was highest in 2000 while NH_4-N was highest in 1998, dropped in 1999 then increased in 2000. Soil NO_3-N and NH_4-N will change with many factors such as time in season sampled (Epstein et al. 1976) or soil moisture. In this case the large change may be due to sampling error as the 2000 NO_3-N and NH_4-N data were lost and rerun in 2004. The lab method used was consistent but the long storage time may have led to increased mineralization if soils had become damp during storage (Mulvaney 1996).

The impact of treatment on total N changed little at depths >15 cm and NO_3-N and NH_4-N were only measured in the upper 15 cm. Other studies found movement of N from the area of incorporation to lower depths (Barbarick et al. 1996, Epstein et al. 1976) indicating NO_3-N leaching may be occurring.

For all forms of N measured the inorganic amended fertilizer treatment showed no significant treatment response and did not differ from that of the control. Stroo and Jencks (1982) found some initial response to fertilizer addition but this did not last over time. Seaker and Sopper (1988) also noted a limited response of soil N to fertilizer addition when compared to biosolids amendments. This is likely due to the mineral forms of N being quite soluble and easily lost via leaching and volatilization while biosolids contain mainly organic forms (Henry et al. 1991).

3.1.2 Total and available phosphorus

Both total and available P increased with increasing biosolid additions, showing a mainly linear response (Table 3.9 and 3.10). Biosolids addition at the higher rates increased total P levels beyond that of the average for sand and silt loam soils (Table 3.5). The fertilizer treatment did not significantly differ from that of the control but the biosolids 150 Mg ha^{-1} treatment was significantly different from the fertilizer treatment, showing a response to biosolids but not fertilizer. Topper and Sabey (1986) noted similar results with lack of response from inorganic fertilizer vs biosolids addition for available P. The response for total P was similar to that found by Hinesly et al. (1982) although their values were higher. For the lowest treatment level in their study (224 Mg ha^{-1} biosolids) the average total P concentration was 7800 ppm vs a three year average of 4070 and 3220 ppm at our silt loam and sand sites, respectively, for the biosolids 250 Mg ha^{-1} treatment. Griebel et al. (1979) found no relationship between biosolids and total soil P when biosolids were applied to an acid strip mine at rates of 56, 112 and 224 Mg ha^{-1}.

The mainly linear response demonstrated for available P with increasing biosolid additions was in agreement with studies conducted by Tsadilas et al. (1995), Topper and

Sabey (1986) and Epstein et al. (1976). Fanco-Hernandez et al. (2003) noted no increase in available P when different biosolids treatments were applied vs an unamended control. The values from Topper and Sabey (1986) and Epstein et al. (1976) exceeded those in our study. Epstein et al. (1976) used the Bray method to determine available P and found an average 253 ppm for the 240 Mg ha^{-1} application rate while our values (average of three years) were 28 and 56 ppm available P for the silt loam and sand sites, respectively. Topper and Sabey (1986) used the AB-DTPA extraction method to determine available P and found 106 ppm at 55 Mg ha^{-1} biosolids treatment rate vs our average three year value of 23 and 36 ppm available P for the silt loam and sand sites for the biosolids 50 Mg ha^{-1} treatment. Epstein et al. (1976) found a soil test exceeding 20 ppm of available P is considered high. Therefore values in excess would not be considered beneficial for plant uptake and may even result in excess P which can lead to eutrophication of nearby water bodies through runoff.

P in the sludge can be both organic and inorganic (Brady and Weil 1996). Organic forms will release more gradually via mineralization and thus will be more available for plant uptake (Brady and Weil 1996) than that in the inorganic form, which is likely to bind with Ca in the alkaline tailings environment. Even in the unamended control, plant available P was fairly high and thus P is not likely a limiting nutrient to plant growth in these tailings. Treatment response was mainly confined to the upper 0 to 15 cm where biosolids were incorporated. Both total and available P remained high over the three years of the study. Epstein et al. (1976) noted a similar response over the two year period of their study. Treatment response was more pronounced for the sand than the silt loam tailings (Table 3.9 and 3.10).

3.1.3 Total sulfur

In both sites and in all years, total S increased with increasing biosolids. The inorganic fertilizer treatment did not differ significantly from the control while the fertilizer treatment was significantly different from the biosolids 150 Mg ha^{-1} treatment (Table 3.11). For the control our values were similar to that of a normal soil (Table 3.5). Over time total S in the biosolids treatments decreased slightly, with a more notable response from the silt loam than than the sand site. Little information is available in the literature on biosolids addition and total S. Increasing biosolids increased soil total S as biosolids contain sulfur containing materials such as proteins, which will contribute to total organic S in soil (Tisdale et al. 1985). The difference in total S behaviour over time at the two sites may be a response to soil conditions such as aeration and moisture. At the silt loam site, mineralization may have been higher initially and therefore resulted in more significant losses via leaching of inorganic sulfate or volatilization of sulfide than at the sand site. Plant growth in 1999 and 2000 may also have removed S from the soil. The silt loam site had higher plant growth than the sand site.

3.1.4 Total and available potassium

Total K of the tailings material was not impacted by biosolid or inorganic fertilizer additions. Total K averaged over three years ranged from 0.15 to 0.16% at the silt loam site and 0.07 to 0.08 % at the sand site, below the mean for sand and silt loam soils (Table 3.5) and there was no year response. Sites were different with the sand site having lower levels but there was no significant location by treatment effect. Total K in sewage sludge is often low because most K is removed with the effluent portion since it is highly soluble (Brady and Weil 1996). In his review of the biosolid literature Sopper (1993) noted that in general biosolids have a small effect on soil K. Hinesly et al. (1982) reported a significant decrease in total K with increasing rates of biosolid additions up to 448 Mg ha^{-1}. Their average values were higher than those from this study, ranging from 2.4 in the control to 1.8 in the 448 Mg ha^{-1} biosolids treatment. Others researchers found a significant linear increase in total K with increasing biosolids additions (Fresquez et al. 1990a and 1990b). An increase in available K was found at the sand tailings in the upper 15 cm of the soil and a treatment response was found in the silt loam tailings only in 1998, the first year of application (Table 3.12).

3.1.5 Total calcium

Total Ca showed a treatment response in the upper 15 cm of tailings on the sand site (Table 3.13) and this increase was small. Total Ca in the control at both sites was similar to that found in sand and silt loam soils (Table 3.5). As noted in Chapter II, the cation exchange capacity (CEC) sites were dominated by exchangeable Ca and plant availability to this nutrient was not limiting. Epstein et al. (1976) also found a similar increase in exchangeable Ca with biosolids application. Sopper (1993), in his review of the literature on biosolids, reported Ca contribution can vary depending on biosolids composition but increases of Ca were noted.

3.1.6 Total magnesium

Total Mg had a linear response to biosolid additions while the control and fertilizer amended treatments did not differ. The biosolids 150 Mg ha^{-1} and fertilizer treatments were significantly different (Table 3.13). The response to treatment was similar between sites, however sites were significantly different ($p=0.0001$). Mg remained similar between years. Normal Mg levels at similar soil textures are an order of magnitude higher (Table 3.5), indicating that even with a treatment response values may be limiting to plant growth. In Chapter III it was noted that levels of exchangeable Mg^{+2} were lowest of the base cations measured.

3.2 Micronutrients

3.2.1 Total boron

No clear B response to treatment was found. However, there was a significant year response with B highest in 1998, averaging 25 ppm at the silt loam site and 35 ppm at the sand site, then decreasing slightly for 1999 and 2000. Boron is quite mobile and susceptible to leaching loss (McBride 1994), although no movement of B was found with depth. Total B (mean of the three years sampled) averaged 18 ppm at the silt loam site and 23 ppm at the sand site, falling within the normal range for mineral soils (Table 3.5). Boron concentrations were significantly ($p=0.0116$) higher in sand than silt loam tailings.

3.2.2 Total cobalt

No treatment, year or site effect was found for total Co. Values were below 1.5 ppm which is at the low end of the range normally found in mineral soils (Table 3.5). Soils with a Co concentration of less than 5 ppm may result in vegetation that is deficient in Co for animals (Kabata-Pendias and Pendias 1992). Large amounts of Mn or Fe oxides in the soil, alkaline conditions and soils with high organic matter can all be factors contributing to Co deficiency for grazing animals (Kabata-Pendias and Pendias 1992).

3.2.3 Total and available copper

Total Cu showed no treatment response but differed significantly over years (p=0.0001) and between sites (p=0.0031). Average total Cu at the silt loam site was 665 ppm and at the sand site was 1313 ppm, well above the normal range for soils (Table 3.5). Copper concentrations were similar among years but showed a slight increase in 2000. Hinesly et al. (1982) and Griebel et al. (1979) found a significant increase in soil Cu with increasing biosolids, however their control treatments had lower levels of Cu (27 ppm and 18 ppm, respectively). Sopper (1993) summarized several studies that assessed metal concentration with biosolids application and all noted a significant increase in Cu. The lack of response of total Cu to biosolids treatment at our study sites is likely due to the high Cu in the tailings to begin with.

Available Cu showed little impact due to treatment. The only significant response (p=0.0223) was at 0 to 15 cm on sand tailings in 1998 where increased biosolids resulted in decreased available Cu. There were no significant differences between sites. However, there was a treatment by location interaction (p=0.0053) as decreasing availability with increased biosolids addition was found at the sand site and only a slight (but not significant) decreasing trend was found at the silt loam site. The range of available Cu was 132 to 145 ppm at the silt loam site and 144 to 223 ppm at the sand site. Sanchez-Monedero et al. (2004) found addition of biosolids combined with cotton waste materials and applied at different stages of composting all decreased available Cu vs that in the unamended control. They attributed the decrease to increased complexing of Cu by organic matter. However, Sopper (1993), Tsadilas et al. (1995) and Greibel et al. (1979) all noted increased available Cu with increasing biosolids. Greibel et al. (1979) found available Cu increased from 2.5 ppm in the control to 10, 6 and 20 ppm for composted biosolids application rates of 56, 112 and 224 Mg ha^{-1}, respectively. Our average Cu availability was higher than these values, showing an abundance of available Cu at the sites. High available Cu from amendments is not always reflected in the vegetation (Greibel et al. 1979) as Cu can be bound by organic matter decreasing its bioavailability (Sanchez-Monedero et al. 2004).

3.2.4 Total and available iron

Total Fe responded in a linear fashion to increasing biosolids at the 0 to 15 cm depth (Table 3.14). Treatment was not a factor at depth but sites did differ significantly (p=0.0001). Even with the highest biosolids addition total Fe was below or at the low end of the range for normal Fe soil concentrations (Table 3.5). Iron deficiency is most common on alkaline soils but additions of organic materials may help correct Fe deficiencies by supplying organic chelating agents that increase Fe solubility (Tisdale et al. 1985). Available Fe also increased with increasing biosolids (Table 3.14) indicating organic matter or Fe from biosolids may be contributing to increased Fe solubility. Hinesly et al. (1982) found a similar increase in total Fe with increasing rates of biosolids while Tsadilas et al. (1995) reported no changes in available Fe with increasing biosolids when pH was constant.

3.2.5 Total and available manganese

Total Mn was not impacted by treatment but did differ between sites (p= 0.0001). Total Mn averaged 415 ppm at the silt loam site and 276 ppm at the sand site, which is in the range for normal soils but below average (Table 3.5). These results support those of Hinesly et al. (1982) who found increasing biosolids up to 448 Mg ha^{-1} resulted in no changes to total Mn. Available Mn did respond to treatment and a significant linear response was found for both sites and all years in the 0 to 15 cm depth (Table 3.14). Sites were significantly different (p=0.0016) although treatment response was similar between sites. Tsadilas et al. (1995) reported that at pH 6.5 to 7.5 available Mn is not impacted by increasing biosolids.

3.2.6 Total and available molybdenum

Total Mo in the upper 15 cm of sand tailings decreased with increasing biosolids addition and was significantly different at the silt loam site in 2000 (Table 3.15). Molybdenum levels remained similar throughout the three years but were different between sites. Available Mo only showed a significant treatment response at the silt loam site in 2000 but did show a decreasing trend (Table 3.15). However, available Mo showed no response to treatment at the sand site (Table 3.15). Available Mo was significantly (p=0.0001) impacted by location and treatment response as noted above and was significantly different (p=0.0001) at the two sites.

Globally Mo in soil averages 1 to 2 ppm but in the United States the range is 1 to 40 ppm with an average of 1.2 ppm (Edwards et al. 1995) (Table 3.5). Removal of Mo from mined ore is not 100% efficient thus Mo is concentrated in tailings. Biosolids contain varying levels of Mo and application usually results in increased Mo and availability due to the addition of Mo, and the higher pHs associated with biosolids addition (Edwards et al. 1995). For example, Topper and Sabey (1986) noted an increase in available Mo with increased biosolids. As pH remained high for all treatments in our study (range 7.0 to 7.5) it had little impact on Mo availability over that of the control or inorganic fertilizer treatements. Gupta (1971) noted adding organic materials decreased Mo availability which is similar to the trend for the silt loam site. This decrease may be a result of more Mo being complexed with organic matter. Decreased total Mo may also be due to a dilution effect but why there is more response to treatment at the sand site than the silt loam site is unclear. Decreasing available Mo at the silt loam site may be related to many factors such as higher soil moisture (increased leaching) (Kabata-Pendias and Pendias 1992) or higher plant growth and yield resulting in more plant uptake of available Mo.

3.2.7 Total and available zinc

Total Zn showed a strong linear increase in the biosolids amended soils but not with fertilizer addition (Table 3.15). The treatment response between sites was similar but sites were significantly different (p=0.0001) with the silt loam site having higher average values than the sand site; in all cases total Zn remained in the normal soil range (Table 3.5). Many other studies found a similar increase in total Zn with increasing biosolid amendment (Tsadilas et al. 1995, Hinesly et al. 1982, Griebel et al. 1979). Berti and Jacobs (1996) studied the chemistry of trace elements from sludge application and found large amounts of Zn are in water soluble exchangeable and acid soluble forms increasing plant bioavailability.

Available Zn also showed a significant linear treatment response in the upper 15 cm (Table 3.15). Sites differed (p=0.0095) but no treatment by site interaction was noted. Treatment response to available Zn supports the findings of Sanchez-Monedero et al. (2004), Tsadilas et al. (1995), Griebel et al. (1979) and Peterson et al. (1979). Leita and de Nobili (1991 as cited in Sanchez-Monedero et al. 2004) note that Zn is associated with the more soluble fractions of organic matter, and Zn availability will likely be higher soon after biosolids application and decrease with time. White et al. (1997) found available Zn was higher for soils receiving biosolids than control samples four years after application but by eight years values were similar to the control. Topper and Sabey (1986) found no increase in available Zn with increasing biosolids of up to 83 Mg ha^{-1}. Walter et al. (2002) reported that total Zn concentration increased after initial bisolid application then decreased by year 5 while available Zn showed varaible results depending on type of biosolids used. They attributed these differences to different rates of decomposition of organic matter between the two biosolid products applied.

3.3 Other Elements

Soil As contents for both sites in all years remained below 5.0 ppm which is below the average soil level (Table 3.5). Therefore, As concentration on the tailings site is not considered an element of concern. Cadmium also did not show a treatment response, time effect or site response. All values remained below 1.5 ppm which is within the range normally found in soil (Table 3.5).

No treatment response was found for Cr which at the silt loam site ranged from 20 to 33 ppm and at the sand site ranged from 41 to 49 ppm. There was a year response with Cr highest in 1998, averaging 37 ppm at the silt loam site and 74 ppm at the sand site then dropping to slightly lower values in 1999 and 2000. In all cases the concentration was at the lower end of the range for normal soils (Table 3.5). Hinesly et al. (1982) noted an increase in Cr with increasing sewage sludge addition, with an average value of 390 ppm for an addition rate of 224 Mg ha^{-1}. Tsadilas et al. (1995) found a similar increase using a variety of soil extraction methods.

Total soil Ni showed a significant linear response to treatment (Table 3.16) with fertilizer and control treatments not differing significantly. Nickel was only determined in 1999 and 2000 and values remained similar over these two years. The two locations differed significantly (p= 0.0001) but no treatment by location interaction was found. The average total Ni level tends to be lower for sands vs silt loams (Table 3.5), which is the trend that our sites exhibit although the concentrations were lower. Berti and Jacobs (1996), Tsadilas et al. (1995), Hinesly et al. (1982), Griebel et al. (1979) and Peterson et al. (1979) all found increased soil Ni with biosolids amendments.

Total Pb increased linearly with increasing biosolids but did not respond to fertilizer (Table 3.16). Site effect was significant (p=0.0001) with the silt loam site showing consistently higher values than the sand site; concentrations at both sites fell in the normal soil range (Table 3.5). Increases in Pb are common after addition of biosolids (Sanchez-Monedero et al. 2004, Tsadilas et al. 1995, Seaker 1991, Topper and Sabey 1986, Hinesly et al. 1982). Values for our highest biosolids treatment rate of 250 Mg ha^{-1} were lower than those noted by Hinesly et al. (1982) who had a higher level in the control (15 ppm total Pb) and observed an increase to 134 ppm with application of 224 Mg ha^{-1} of biosolids. White et al. (1997) found Pb was higher than a control treatment four years after biosolid application but after eight years values were similar while Walter et al. (2002) reported that total Pb concentration increased after initial bisolid application then decreased by year 5.

3.4 Movement of Elements

The movement of the elements in the soil profile is a concern with biosolid application. This study did not directly compare elements at the three depths sampled but treatment response to the majority of the elements was focused in the upper 0 to 15 cm of the tailings. Little response to treatment was found at 15 to 30 and 30 to 45 cm depths suggesting over the three year period of this study little movement of elements below the depth of biosolids incorporation occurred. These findings support those of Seaker (1991) who found metallic elements remained in the plow layer although there was slight movement to 15 to 30 cm depths. A literature review by Harrison et al. (1991) stated that trace metals remained mainly in the layer of biosolids incorporation, even at applications up to 476 metric tons ha^{-1}. Gove et al. (2001) studied the movement of the heavy metals Zn, Cu, Pb and Ni through a sand and sandy loam soil amended with biosolids and found no difference in metal losses between amended and unamended soils. Barbarick et al. (1998) found an increase in available Zn below the upper 20 cm with biosolids addition and other studies found mobility of many metals increased at lower pH levels (Harrison et el. 1991).

3.5 Fertilizer versus Biosolids Amendment

In all cases where a significant treatment effect was found the orthogonal contrasts showed inorganic fertilizer amended treatments did not differ significantly from the unamended treatment. Thus fertilizer is having no significant impact on soil chemistry at either study site which may be due to a variety of factors. Fertilizer was applied only once (spring 1999) and larger and more frequent applications may be required to show a treatment response. Inorganic forms in fertilizer are usually more mobile than some organic forms in biosolids (Brady and Weil 1996) and can therefore be removed from the system quite rapidly. As noted in Chapter II, biosolid treatments increased corresponding CEC and have an overall impact on soil physical properties. Other studies also found limited to no treatment response with inorganic fertilizers vs organic amendments (Seaker and Sopper 1988, Stroo and Jencks 1982).

3.6 Site Differences: Sand versus Silt Loam

Available Fe, K, Mn, Mo, NO_3-N, Zn and total C, Ca, Fe, K, Mg, Mn, Mo, N, Ni, P, Pb, S and Zn were all higher at the silt loam site than the sand site. For sand soils low in organic matter, metal adsorption is often low (Gove et al. 2001). Available P and total B, Cr and Cu were significantly higher at the sand site. As discussed in Chapter II, the sites have similar soil pH but differ in texture, organic matter, CEC, electrical conductivity, bulk density, moisture and water holding capacity. In general, the higher CEC at the silt loam site will result in an enhanced ability to hold nutrients (Brady and Weil 1996). Some of the site differences in elements present may be related to the milling process that occurred at the two different tailings ponds or the ore body being mined.

In general, the response to treatment was similar between sites, although sometimes the treatment effect would be more pronounced at one site or the response over time might vary between sites. For example, there was a greater increase with increasing biosolids addition for available P and total B at the sand site than at the silt loam site.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

- A one time incorporation of biosolids applied to alkaline Cu and Mo mine tailings beneficially increased total loading of most macronutrients and micronutrients regardless of rate of application.
- Biosolid addition lowered the high tailings Mo levels, decreasing total Mo at the sand site and available Mo at the silt loam site.
- The addition of biosolids only increased total P to concentrations considered outside of the normal soil range.

- In all cases, the control treatment did not vary from that of the inorganic fertilizer amendment, indicating that the fertilizer had no measurable impact on the soil element concentrations.
- The benefits of biosolids addition continued over the three years of the study as evidenced by the majority of the elements not changing in concentration over the three years of the study.
- Treatment response was mainly confined to the layer of biosolids incorporation, the upper 15 cm of tailings, indicating little movement of the elements in the soil profile and leaching of the elements from the sites.
- Response to biosolid addition was similar between the two different textured sites indicating that the response in soil element levels is due more to the biosolids added than to the tailings.

4.2 Management Recommendations

- A one time surface application of inorganic fertilizer is not sufficient to ameliorate the nutrient limitations at these sites so that vegetation can be established successfully while biosolid applications were effective over a three year period.
- The rate of biosolid application that is most biologically and cost effective will depend on the nutrient limitations of the site in question. At both sites, a rate of 50 Mg ha^{-1} may be sufficient to increase many of the soil elements but at the sand site low initial levels of such elements as N and S may require higher application rates.
- Movement of elements in the soil profile at both sites is limited as is increase in most metals of concern. Rates of up to 250 Mg ha^{-1} can therefore be applied without concern for the negative impacts from potential element leaching.
- Adding biosolids to high Cu and Mo tailings does not increase these elements and in the case of total soil Mo results in a reduction.

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Table 3.1. Climate information at the tailings sites over the three years from the Lornex weather station (C.E. Jones and Associates 1999, 2000 and 2001).

Variable	1998	1999	2000
Snowfall from Nov 1-March 31 (cm)	88	157	77
Rainfall from Nov 1-March 31 (mm)	77	59	25
Precipitation from April-Oct (mm)	182	172	386
Temperature range from April-Oct (°C)	-6.5 to 33	-11 to 28	-8.5 to 28
Growing degree days	1509	975	1037
Frost free period (days)	173	136	169
Monthly mean annual minimum temperature (°C)	-5 (Jan)	-5 (Dec)	-5 (Dec)
Monthly mean annual maximum temperature (°C)	17.5 (Aug)	15 (Aug)	15 (July)

Table 3.2. Mean values of elements from chemical analysis of biosolid stockpiles at silt loam and sand sites and average values from the Greater Vancouver Regional District (GVRD) biosolids.

Element	Silt Loam Site Stockpile	Sand Site Stockpile	GVRD Average Values
Macronutrients			
Total C (%)	29.1	31.3	-
Total Ca (%)	2.5	2.5	-
Total K (%)	0.1	0.1	0.1
Total Mg (%)	0.5	0.4	0.4
Total N (%)	4.0	4.2	4.7
Total P (ppm)	>1000.0	>1000.0	22,400.0
Available NH_4-N (ppm)	20.6	22.6	8990.0
Available NO_3-N (ppm)	5.3	1.6	8.7
Micronutrients			
Total B (ppm)	39.0	37.5	28.9
Total Co (ppm)	5.5	4.0	4.6
Total Cu (ppm)	969.0	967.0	743.0
Total Fe (%)	110.0	105.0	1.3
Total Mn (ppm)	366.0	311.0	328.0
Total Mo (ppm)	10.0	10.5	10.4
Total Zn (ppm)	959.0	982.0	912.0
Other Elements			
Total As (ppm)	10.0	7.5	14.2
Total Cd (ppm)	6.0	5.5	3.5
Total Cr (ppm)	70.5	64.0	63.6
Total Ni (ppm)	25.5	25.5	27.7
Total Pb (ppm)	110.0	105.0	69.4

GVRD - Greater Vancouver Regional District, source for the biosolids used in this study

Table 3.3. Fertilizer treatment used at the silt loam and sand sites on the inorganic fertilizer plots.

Element	Form	Application Rate (kg ha^{-1})
N	Ammonium nitrate (34.5%)	86.9
P	Phosphoric acid (45%)	111.1
K	Potassium chloride (60%)	83.3
Zn	Zinc chloride (99.9%)	0.5
B	Granular boron (14.3%)	21.0

Table 3.4. Soil total nitrogen (%) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	0.016	0.009	0.011	0.005	0.020	0.020
Fertilizer	*0.011	0.005	*0.006	0.001	*0.021	0.010
Biosolids 50	0.170	0.087	0.081	0.105	0.151	0.088
Biosolids 100	0.303	0.130	0.162	0.133	0.246	0.135
Biosolids 150	*0.600	0.100	*0.200	0.230	*0.350	0.121
Biosolids 200	0.681	0.122	0.248	0.211	0.431	0.110
Biosolids 250	0.935	0.205	0.394	0.323	0.471	0.088
p value	0.0001 linear		0.0001 linear		0.0001 linear	
Sand Site						
Control	0.003	0.000	0.006	0.003	0.003	0.001
Fertilizer	*0.003	0.001	*0.006	0.001	*0.004	0.001
Biosolids 50	0.117	0.045	0.059	0.027	0.062	0.048
Biosolids 100	0.188	0.083	0.151	0.079	0.108	0.035
Biosolids 150	*0.333	0.065	*0.182	0.071	*0.187	0.076
Biosolids 200	0.524	0.158	0.257	0.124	0.239	0.054
Biosolids 250	0.815	0.250	0.425	0.159	0.300	0.073
p value	0.0001 linear		0.0001 linear		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.5. Reported levels of total elements in mineral soil.

Element	Sand-Range (mean)	Silt Loam-Range (mean)	Normal Soil Range	Average Soil Level	Reference
N (%)	(0.03)	(0.4)	0.02 – 0.5	0.15	1, 2
P (ppm)	(200)	(1000)	-	-	1
S (%)	(0.06)	(0.12)	-	-	1
K (%)	(1.9)	(1.9)	-	-	1
Ca (%)	(1.2)	(3.0)	-	-	1
Mg (%)	(0.1)	(2.0)	-	-	1
B (ppm)	-	-	2-100	10	3
Co (ppm)	-	-	1-40	8	3
Cu (ppm)	1-70 (13)	4-100 (23)	2-100	20	3, 4
Fe (%)	-	-	0.7-55	3.8	5
Mn (ppm)	-	-	100-4000	850	3
Mo (ppm)	-	-	1-40	1.2	6
Zn (ppm)	-	-	10-300	50	3
As (ppm)	<0.1-30 (4.4)	1.3-27 (8.4)	0.1-40	6	3, 4
Cd (ppm)	0.01-27 (0.37)	0.08-1.61 (0.45)	0.01-7	0.06	3, 4
Cr (ppm)	1.4-530 (47)	4-1,100 (51)	5-3000	100	3, 4
Ni (ppm)	1-110 (13)	3-110 (26)	10-100	40	3
Pb (ppm)	2.3 – 70 (22)	1.5 – 70 (28)	2-200	10	3, 4

1 Tisdale et al. 1993, 2 Brady and Weil 1996, 3 Allaway 1968,
4 Kabata-Pendias and Pendias 1992, 5 Tisdale et al. 1985, 6 Edwards et al. 1995

Table 3.6. Soil carbon to nitrogen ratio for 0 to 15 cm.

Site	Treatment	1998	1999	2000
Silt Loam Site	Control	42.4	54.5	36.3
	Fertilizer	56.0	90.2	37.6
	Biosolids 50	10.7	14.8	13.6
	Biosolids 100	8.9	10.7	12.0
	Biosolids 150	7.8	10.2	10.7
	Biosolids 200	7.7	9.3	10.3
	Biosolids 250	7.4	8.5	10.1
Sand Site	Control	100.0	47.5	90.3
	Fertilizer	98.3	48.0	72.0
	Biosolids 50	10.0	13.1	13.1
	Biosolids 100	8.6	9.7	11.4
	Biosolids 150	7.6	9.6	10.5
	Biosolids 200	7.3	8.9	10.0
	Biosolids 250	7.1	8.1	9.8

N = 8 for each year and 24 for mean of years

Table 3.7. Soil available nitrate (ppm) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	1.45	0.77	2.06	1.27	6.13	3.25
Fertilizer	*1.48	1.12	*0.56	0.39	*25.34	66.18
Biosolids 50	11.16	7.91	18.69	8.66	20.31	44.75
Biosolids 100	31.92	16.71	47.61	14.67	40.11	32.16
Biosolids 150	*71.49	12.69	*60.55	22.99	*105.59	75.29
Biosolids 200	90.54	27.30	67.51	8.81	135.59	58.65
Biosolids 250	131.53	31.09	85.94	26.96	215.69	138.86
p value	0.0001		0.0001		0.0001	
	linear		linear		linear	
Sand Site						
Control	0.21	0.14	0.14	0.07	1.14	0.70
Fertilizer	*0.19	0.08	*0.69	1.24	1.26	0.97
Biosolids 50	3.38	2.04	7.16	3.04	13.81	25.73
Biosolids 100	12.21	5.12	17.21	9.90	7.91	10.54
Biosolids 150	*37.40	13.25	*21.80	5.92	22.73	19.56
Biosolids 200	59.28	12.14	30.68	15.04	49.43	36.99
Biosolids 250	76.34	25.37	59.20	31.71	79.97	54.45
p value	0.0001		0.0001		0.0001	
	quadratic		quadratic		quadratic	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.8. Soil available ammonium (ppm) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	0.43	0.38	0.18	0.07	7.17	6.67
Fertilizer	*0.74	0.70	*0.30	0.23	*4.05	3.68
Biosolids 50	23.61	9.15	0.84	0.42	8.57	6.30
Biosolids 100	40.96	10.52	1.74	0.76	7.88	6.96
Biosolids 150	*79.78	36.60	*2.10	0.62	*20.56	10.07
Biosolids 200	77.29	36.24	4.04	2.18	19.07	10.66
Biosolids 250	71.92	35.16	4.46	1.53	20.77	9.56
p value	0.0001 quadratic		0.0001 linear		0.0002 linear	
Sand Site						
Control	0.28	0.07	0.10	0.04	3.44	2.87
Fertilizer	0.38	0.31	*0.09	0.21	*2.94	2.96
Biosolids 50	22.99	9.01	0.61	0.50	5.42	6.64
Biosolids 100	34.18	13.88	1.49	0.70	8.31	3.94
Biosolids 150	57.25	15.93	*2.46	1.13	*14.85	8.96
Biosolids 200	172.66	342.88	3.78	1.93	11.56	9.03
Biosolids 250	77.91	25.07	9.65	4.48	14.80	8.15
p value	0.1409		0.0001 quadratic		0.0008 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference (p<0.05) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.9. Soil total phosphorus (ppm) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	371	68	314	61	450	166
Fertilizer	*335	45	*336	71	*439	51
Biosolids 50	1156	393	1138	533	1568	709
Biosolids 100	1723	553	1556	628	2336	1122
Biosolids 150	*3125	510	*2566	1081	*3054	943
Biosolids 200	3533	492	2530	862	3850	944
Biosolids 250	4525	951	3621	842	4064	829
p value	0.0001 linear		0.0001 linear		0.0001 linear	
Sand Site						
Control	291	34	311	47	323	79
Fertilizer	*286	47	*320	45	*364	117
Biosolids 50	853	227	650	151	843	376
Biosolids 100	1185	386	1090	555	1240	380
Biosolids 150	*1791	260	*1418	405	*1935	525
Biosolids 200	2596	632	1766	579	2241	510
Biosolids 250	3770	936	2810	900	3081	775
p value	0.0001 quadratic		0.0001 linear		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.10. Soil available phosphorus (ppm) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	13.0	3.8	15.5	4.1	18.3	4.8
Fertilizer	*12.7	4.3	*15.9	4.9	*20.8	5.4
Biosolids 50	21.7	4.9	21.2	5.3	27.1	6.6
Biosolids 100	10.1	3.9	29.5	10.3	28.4	8.4
Biosolids 150	*18.3	3.0	*23.9	5.0	*32.3	13.7
Biosolids 200	18.7	3.7	26.7	7.6	42.0	19.3
Biosolids 250	20.1	2.5	29.1	9.3	35.9	11.1
p value	0.0001 quadratic		0.0003 linear		0.0001 linear	
Sand Site						
Control	18.0	8.5	19.4	12.6	24.5	16.3
Fertilizer	*20.4	8.8	*21.1	9.5	*32.0	20.1
Biosolids 50	36.1	6.4	32.7	10.0	37.9	11.6
Biosolids 100	45.8	9.1	37.4	15.4	47.7	18.3
Biosolids 150	*44.2	7.7	*54.8	7.2	*58.4	19.5
Biosolids 200	38.9	5.4	56.8	9.7	62.3	25.0
Biosolids 250	38.3	5.9	57.7	7.6	70.6	19.6
p value	0.0001 quadratic		0.0001 linear		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.11. Soil total sulfur (%) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	0.151	0.022	0.138	0.064	0.103	0.036
Fertilizer	*0.137	0.036	*0.113	0.057	*0.115	0.052
Biosolids 50	0.201	0.076	0.163	0.069	0.131	0.041
Biosolids 100	0.228	0.047	0.175	0.071	0.150	0.039
Biosolids 150	*0.332	0.040	*0.215	0.067	*0.180	0.040
Biosolids 200	0.341	0.029	0.195	0.043	0.173	0.034
Biosolids 250	0.407	0.083	0.263	0.044	0.188	0.054
p value	0.0001 linear		0.0001 linear		0.0001 linear	
Sand Site						
Control	0.068	0.020	0.067	0.017	0.056	0.020
Fertilizer	*0.066	0.014	*0.057	0.012	*0.051	0.014
Biosolids 50	0.092	0.013	0.065	0.011	0.060	0.021
Biosolids 100	0.116	0.032	0.094	0.026	0.070	0.016
Biosolids 150	*0.158	0.019	*0.095	0.015	*0.081	0.031
Biosolids 200	0.203	0.044	0.112	0.024	0.096	0.019
Biosolids 250	0.271	0.053	0.152	0.044	0.102	0.012
p value	0.0001 quadratic		0.0001 quadratic		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.12. Soil available potassium (ppm) means for 0 to 15 cm.

Treatment	1998	SD	1999	SD	2000	SD
Silt Loam Site						
Control	125.6	18.8	110.6	33.7	113.4	29.3
Fertilizer	*124.4	34.7	109.4	49.7	116.8	33.4
Biosolids 50	141.2	52.4	97.3	54.1	95.3	44.9
Biosolids 100	177.0	41.6	101.4	45.1	101.2	28.0
Biosolids 150	*192.3	32.4	88.2	43.8	121.3	25.2
Biosolids 200	188.5	30.0	86.6	35.8	113.8	28.0
Biosolids 250	207.9	28.4	101.0	37.6	112.5	32.0
p value	0.0001 linear		0.1856		0.3351	
Sand Site						
Control	1.4	1.4	5.8	0.9	8.3	2.0
Fertilizer	*1.3	1.2	*9.4	3.3	*12.0	6.5
Biosolids 50	8.8	4.4	10.5	3.3	12.4	5.2
Biosolids 100	17.5	6.6	11.9	4.9	14.8	4.8
Biosolids 150	*32.8	4.9	*16.4	3.4	*20.1	7.7
Biosolids 200	42.5	11.6	20.6	5.9	19.6	7.1
Biosolids 250	67.4	18.2	31.3	11.2	30.6	7.1
p value	0.0001 quadratic		0.0001 quadratic		0.0001 linear	

N = 8 for each year and 24 for mean of years

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 3.13. Soil total calcium and magnesium (%) for the means of the three study years for 0 to 15 cm.

Site	Treatment	Total Ca (%)	SD	Total Mg (%)	SD
Silt Loam Site	Control	1.86	0.23	0.13	0.02
	Fertilizer	1.84	0.23	0.13	0.03
	Biosolids 50	1.90	0.25	0.14	0.03
	Biosolids 100	1.92	0.26	0.14	0.03
	Biosolids 150	1.94	0.22	0.16	0.03
	Biosolids 200	1.88	0.19	0.16	0.03
	Biosolids 250	1.93	0.18	0.18	0.03
Treatment	p value	0.2951		0.0001	
Sand Site	Control	0.93	0.05	0.05	0.01
	Fertilizer	0.94	0.06	0.05	0.01
	Biosolids 50	0.95	0.07	0.06	0.01
	Biosolids 100	0.96	0.08	0.06	0.01
	Biosolids 150	1.01	0.07	0.07	0.01
	Biosolids 200	1.01	0.10	0.08	0.02
	Biosolids 250	1.08	0.10	0.09	0.02
Treatment	p value	0.0001		0.0001	

N = 24 for all treatments
SD = standard deviation

Table 3.14. Soil total iron (%), available iron (ppm) and available manganese (ppm) for the means of the three study years for 0 to 15 cm.

Site	Treatment	Total Fe (%)	SD	Avb. Fe (ppm)	SD	Avb. Mn (ppm)	SD
Silt Loam Site	Control	0.74	0.12	58.8	10.6	1.8	0.6
	Fertilizer	0.76	0.12	56.8	13.7	1.8	0.7
	Biosolids 50	0.79	0.13	59.7	10.1	2.9	1.1
	Biosolids 100	0.81	0.13	58.9	12.4	4.0	1.4
	Biosolids 150	0.88	0.12	65.2	12.9	5.4	2.4
	Biosolids 200	0.89	0.12	70.1	14.2	7.1	2.7
	Biosolids 250	0.94	0.12	68.2	14.3	8.8	3.9
Treatment	p value	0.0001		0.0001		0.0001	
Sand Site	Control	0.60	0.08	18.1	5.0	1.8	0.5
	Fertilizer	0.59	0.10	17.9	5.7	1.9	0.8
	Biosolids 50	0.58	0.08	23.8	7.0	2.4	0.6
	Biosolids 100	0.61	0.09	24.6	8.2	3.1	1.0
	Biosolids 150	0.63	0.09	29.9	7.4	4.7	1.0
	Biosolids 200	0.64	0.09	33.2	9.3	5.5	1.7
	Biosolids 250	0.68	0.08	38.9	8.8	7.9	2.2
Treatment	p value	0.0001		0.0001		0.0001	

N = 24 for all treatments
SD = standard deviation
Avb. = available

Table 3.15. Soil total and available molybdenum and zinc (ppm) for the means of the three study years for 0 to 15 cm.

Treatment	Total Mo	SD	Avb. Mo	SD	Total Zn	SD	Avb. Zn	SD
Silt Loam Site								
Control	34.5	7.3	5.52	1.97	18.8	5.6	1.9	2.2
Fertilizer	32.0	7.6	4.88	2.04	18.5	4.9	1.9	1.8
Biosolids 50	31.4	9.4	2.47	2.09	59.0	24.7	8.1	5.8
Biosolids 100	31.4	8.5	3.99	1.76	84.8	33.5	12.9	4.6
Biosolids 150	31.7	9.3	4.06	1.65	136.4	42.4	20.1	11.5
Biosolids 200	27.2	6.4	3.41	1.24	151.2	37.4	24.8	11.6
Biosolids 250	28.6	6.5	3.47	1.35	187.2	45.6	30.0	10.9
p value	0.0734		0.0129		0.0001		0.0001	
Sand Site								
Control	18.8	7.2	0.23	0.08	12.6	5.5	0.7	0.3
Fertilizer	19.0	6.7	0.23	0.09	11.3	4.8	1.5	3.2
Biosolids 50	14.7	6.2	0.18	0.07	33.8	12.1	5.6	2.3
Biosolids 100	13.5	4.7	0.22	0.08	50.4	21.1	8.8	4.8
Biosolids 150	13.3	2.6	0.21	0.07	76.5	18.5	15.3	4.4
Biosolids 200	13.0	3.9	0.23	0.06	100.0	30.9	18.2	6.5
Biosolids 250	11.5	3.5	0.25	0.08	149.0	46.7	27.5	9.7
p value	0.0001		0.1601		0.0001		0.0001	

N = 24 for all treatments
SD = standard deviation
Avb. = available

Table 3.16. Soil total nickel and lead (ppm) mean of years sampled for 0 to 15 cm.

Site	Treatment	Ni	SD	Pb	SD
Silt Loam Site	Control	5.56	2.49	5.01	3.94
	Fertilizer	5.38	2.39	5.69	4.34
	Biosolids 50	6.75	2.96	9.22	4.78
	Biosolids 100	6.63	2.98	11.57	5.42
	Biosolids 150	8.38	3.91	16.95	5.34
	Biosolids 200	8.88	3.97	18.54	6.70
	Biosolids 250	9.13	4.05	22.20	6.30
Treatment	p value	0.0001		0.0001	
Sand Site	Control	2.69	1.19	4.33	3.93
	Fertilizer	2.38	0.97	4.67	3.95
	Biosolids 50	2.88	1.22	4.52	2.81
	Biosolids 100	3.19	1.56	6.17	4.34
	Biosolids 150	4.25	2.01	8.63	3.98
	Biosolids 200	4.38	1.75	9.93	5.16
	Biosolids 250	5.06	2.31	13.48	6.55
Treatment	p value	0.0001		0.0001	

N= 16 for Ni and 24 for Pb
SD = standard deviation

IV. INFLUENCE OF BIOSOLIDS AND FERTILIZER AMENDMENTS ON PLANT NUTRIENTS AND COMPOSITION IN REVEGETATED TAILINGS

ABSTRACT

A three-year field study was conducted on two mine tailings sites of silt loam and sand textures, at the Highland Valley Copper mine in Logan Lake, British Columbia to determine the effects of fertilizer and biosolids amendments on vegetation yield, composition and chemistry. Biosolids were applied at dry matter rates of 50, 100, 150, 200 and 250 Mg ha^{-1} and inorganic fertilizer was applied at a nutrient rate similar to the biosolids 150 Mg ha^{-1} treatment. Species seeded were pubescent wheatgrass (*Agropyron trichophorum* (Link) Richt.), orchard grass (*Dactylis glomerata* L.), creeping red fescue (*Festuca rubra* L. var. *rubra*), Russian wild ryegrass (*Elymus junceus* Fisch.), alfalfa (*Medicago sativa* L.), and alsike clover (*Trifolium hybridum* L.). Biosolid additions increased plant yield with higher production at the silt loam site vs the sand site. Bare ground decreased at both sites with increasing amounts of biosolids. At the silt loam site it was reduced to <3% with just a 50 Mg ha^{-1} application while at the sand site bare ground remained above 60% with the highest biosolids application. At the silt loam site orchard grass dominated at low biosolids application while pubescent wheatgrass dominated at high biosolids application rates. Alfalfa comprised a significant portion of the plant community. Biosolid applications increased plant tissue concentration for N, P, Ca, Mg, Mn and Zn. No change was found for As, B, Cd, Co, Cr, Ni or Pb. Molybdenum decreased with biosolids addition and K, S and Cu showed variable responses. Biosolids addition increased the Cu:Mo ratio in the forage. Plant tissue concentrations of elements decreased from year one to year two, except for Mo, and remained below the maximum tolerance level recommended for consumption by cattle. The fertilizer amendment had minimal impact on plant establishment, yield, composition or chemistry and was similar to the control.

1. INTRODUCTION

The use of biosolids generally results in increased plant productivity and cover (Norland and Veith 1995, Harrison et al. 1991, Fresquez et al. 1990a and 1990b) but can alter plant species composition on a site and may decrease overall plant diversity (Pierce et al. 1998 and Fresquez at al. 1990b). Biosolids increase major plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in the plant tissue (Sopper 1993). Of concern, is the increase of certain micronutrients and other elements that may pose a risk to animals and human health (McBride 2003). In his literature review on biosolids and land reclamation, Sopper (1993) noted general increases in copper (Cu), zinc (Zn), chromium (Cr), lead (Pb), cadmium (Cd) and nickel (Ni) in plants grown on biosolid amended sites. Of particular concern are Cd and Zn as they accumulate in animal organs (Fitzgerald 1982). On mine tailings high in Cu and molybdenum (Mo), Mo also poses a risk to animal health as high levels in forage can lead to molybdenosis (Suttle 1991).

Factors such as pH, soil cation exchange capacity (CEC), soil organic matter, soil texture and temperature and levels of elements in the biosolids all impact potential bioavailability of elements to plants (McBride 2003, Harrison et al. 1991). Korentajer (1991) noted that availability of cationic species such as Cd, Cu, Ni and Zn decreased with higher pHs while availability of anionic elements such as Mo and arsenic (As) increased. Kiekens et al. (1984 as cited in Harrison et al. 1991) found higher uptake of Zn, Ni and Cd by plants grown in sandy vs loam or clay soils. Element uptake by plants is not always linear in response to increasing levels of these elements in the soil, resulting in a plateau effect (Sopper 1993, Hinesly et al. 1982). Plant yield often increases with biosolid applications, with elemental concentration lowered due to a dilution effect from higher productivity (Sopper 1993, Griebel et al. 1979). The increase in nutrients, mainly N, helps increase overall growth and productivity on biosolid amended sites but changes to properties such as CEC and water holding capacity also play a role in increased site productivity (Harrison et al. 1991).

Risks associated with cattle grazing of biosolids amended sites are small but depend on levels of elements such as nitrate (NO_3-N), Cd, Pb and Mo in the forage.

Molybdenum is a metallic transition element that is widely distributed in the earth's crust and is essential for both plants and animals (Ward 1994). Much controversy exists in the literature on the maximum tolerable level of Mo in vegetation for cattle consumption. A maximum tolerable level can be fed for a short time with no effect (NRC 1996) and a value of 5 to 10 ppm for Mo is often quoted in the literature (Suttle 1991, Ward 1994, NRC 1996). Also of importance is the Cu:Mo ratio with values that vary in the literature but often a standard of 2:1 is used (Miltimore and Mason 1971, Fletcher and Brink 1969). A three year study conducted by O'Connor and McDowell (1999) showed application of high quality biosolids applied at agronomic rates to an acid, sandy soil resulted in a small transfer of trace elements to forage and Mo concentrations remained below 3 ppm. O'Connor et al. (2001) conducted a risk assessment to establish Mo standards for land application of biosolids and concluded risk of molybdenosis from biosolids Mo is small. However, McBride et al. (2000) suggests Mo should be used as the metal limiting application of biosolids to agricultural land especially if livestock use is considered.

Disease in cattle due to pathogens in biosolids has not been observed (Fitzgerald 1979, 1982). Documented cases of NO_3-N poisoning as a result of cattle grazing biosolids amended sites have also not be documented (Sopper 1993) but levels of NO_3-N in the plant tissue as a result of biosolids application in some studies have been considered toxic (Joost et al. 1987). Little research has been conducted on the impact of biosolids addition on alkaline tailing sites already containing elevated levels of heavy metals such as Cu and Mo. This research was conducted to study the impact of biosolids and inorganic fertilizer amendments on plant composition, total yield and element uptake on two different textural tailings materials.

2. MATERIALS AND METHODS

2.1 Study Site Description

This research was conducted at the open pit Highland Valley Copper (HVC) mine located approximately 80 km southwest of Kamloops and 210 km northeast of Vancouver, BC, Canada. The mine is located in the Thompson Plateau physiographical subdivision, in an open-ended valley between glacially eroded mountains and glacial overburden covers most of the land as glacial till (Broersma 1997). Highland Valley is a low-grade (0.4%) porphyry copper-molybdenum deposit located in the central part of the late Upper Triassic Guichon Creek batholith (Casseleman et al. 1995). This batholith is a composite, calc-alkaline and I-type intrusion put in place about 210 million years ago (Casseleman et al. 1995). The district has five major porphyry Cu-Mo deposits: Valley, Lornex, Bethlehem, Highmont and JA (Casseleman et al. 1995).

Two different tailings sites on the HVC mine were studied. Prior to disturbance the soils consisted of predominately Gray Luvisols. However, due to the site disturbance the tailings on the site are now considered unclassified, Trojan tailings are located at 1400 m above sea level and are texturally classified as a sand (hereinafter referred to as sand tailings). This pond was milled from Valley pit granodiorite rocks containing 60% plagioclase, 10% K-feldspar, 10% quartz, 8% biotite and minor amounts of other elements including calcite and gypsum. Bethlehem tailings are 1450 m above sea level and are texturally classified as a silt loam (hereinafter referred to as silt loam tailings). This pond was milled from Bethlehem pit granodiorite rocks, containing approximately 60% plagioclase, 10% K-feldspar, 10% quartz, 8% hornblende and minor amounts of other elements including calcite. Both tailing sites are alkaline with a pH of 7 to 8.

The area has a continental climate characterized by warm, dry summers and cool winters; however, more extreme temperatures exist at this site because of the higher elevations. The main factor controlling climate is the rainshadow created in the lee of the Coastal Mountains due to the prevailing easterly flowing air (Hope et al. 1991). Substantial growing season moisture deficits are common and frosts can occur at any time (Hope et al. 1991). Climate normals from the Lornex weather station between 1967 and 1990 indicate that 1998 was a drier than normal year and temperatures were above normal resulting in drought conditions (Table 4.1). The conditions in 1999 were also drier than normal but cooler weather resulted in more effective precipitation during the growing season. The 2000 conditions were wetter than average (69% above normal) while temperatures remained close to normal.

Upon closure of the mine an estimated total of 6,900 ha of land will be disturbed with 2,700 ha of tailings ponds (Freberg and Gould Gizikoff 1999). The primary end land use goal for the tailings sites is cattle and wildlife grazing or forage production (Appendix A).

2.2 Experimental Design and Treatments

The two study sites were established in summer 1998. At each site a randomized complete block design with seven treatments and eight blocks was constructed. Blocks were to deal with a moisture gradient. Each plot was 3 by 7 m and a buffer strip of 1 m was placed between blocks. Treatments consisted of a control (C0), a fertilizer amendment (F0), and dry biosolids at rates of 50, 100, 150, 200 and 250 Mg ha^{-1} (B50, B100, B150, B200 and B250, respectively).

Anaerobically digested sewage sludge (biosolids) from the Greater Vancouver Regional District (GVRD) was stockpiled at each site and samples were collected from each stockpile to determine chemical composition (Table 2.2). Dry weight per volume of biosolids was determined prior to application. Biosolids were applied by volume using an all terrain vehicle (ATV), shovel and rake. Biosolids were left to dry for a 2 week period to ease incorporation by a tractor mounted rototiller into the tailings to a depth of approximately 15 cm. In June 1999 the site was broadcast seeded with a grass legume mix and lightly raked by hand. Species were pubescent wheatgrass (*Agropyron trichophorum* (Link) Richt.), orchard grass (*Dactylis glomerata* L.), creeping red fescue (*Festuca rubra* L. var. *rubra*), Russian wild ryegrass (*Elymus junceus* Fisch.), alfalfa (*Medicago sativa* L.), and alsike clover (*Trifolium hybridum* L.) and seeded at rates to produce 20, 20, 15, 15, 15 and 15% cover of each species, respectively (Table 4.2). Legumes were inoculated with rhizobia prior to seeding. At the time of seeding the inorganic fertilizer was manually broadcast on the fertilized plots but was not incorporated. The fertilizer contained N, P, K, Zn and boron (B) and was formulated to be similar in these nutrients to the biosolids 150 Mg ha^{-1} treatment based on biosolids and soil analysis data from the fall 1998 sampling (Table 3.3).

The short term goal for vegetation establishment was to establish cover and reduce erosion of tailings. The long term goal was to have a sustainable site requiring limited management or additional inputs while allowing grazing on the site. Species were selected for drought tolerance, alkalinity tolerance, erosion control, persistence, and palatability. Seeding rate was determined by estimating the percent desired cover for each species in the mix and then factoring in emergence and survivability information as well as germination information from past studies (Table 4.2). The seed rate calculated from these factors was then doubled to account for any seed losses as broadcast seeding was used.

In 1998, prior to application of biosolids, baseline soil sampling was completed at both sites to test for homogeneity. Soil sampling occurred in mid to late September in 1998, 1999 and 2000 using a random grid and destructive sampling locations were never located in the same area twice. Vegetation sampling was conducted in September of 1999 and 2000 using a random grid and destructive sampling was never located in same area twice.

2.3 Plant Tissue Chemistry

Plant yield data were collected by clipping 10 randomly placed 0.1 m^2 quadrats per plot (experimental unit) as close to the ground as possible. Dry or adhering soil was removed prior to bagging the vegetation. The 10 samples per plot were pooled and weighed on a wet basis then dried for 24 hours at 60 °C and weighed again for dry matter. Samples were then ground to pass through a 1 mm stainless steel sieve using a Wiley Mill. The dried and ground samples were extracted using a strong acid leach (Huang et al. 2004, Hewitt and Reynolds 1990) and analyzed for nutrients (As, B, Cd, Cr, cobalt (Co), Cu, Ca, iron (Fe), K, Mg, manganese (Mn), Mo, Ni, P, Pb, sulfur (S), Zn) using a Thermo Jarrell Ash 61E simultaneous inductively coupled argon plasma atomic emission spectrophotometer (ICP). Total N was determined by dry combustion with the Carlo-Erba instrument (Nelson and Sommers 1996). Samples with limited vegetation could not be used for chemical analysis and where therefore excluded from the results.

2.4 Plant Species Composition

Vegetation sampling was conducted using five randomly placed 0.1 m^2 quadrats per plot (experimental unit) to determine bare ground, canopy cover, frequency and average height. Species that were not one of the six seeded species where placed in the category of other. Areal cover on a species basis was determined from above each quadrat and was not divided by canopy layers. Plants rooted outside the quadrat were counted for cover if they fell within the quadrat. Cover was determined for each of the five quadrats then averaged for total cover for that plot. Bare ground was calculated as 100 minus total cover. Frequency was determined by establishing whether a species was rooted within the quadrat and then calculated by dividing the number of quadrats the species was present in by the total number of quadrats sampled on a per plot basis (five). Height for all vegetation on the plot was determined by using a ruler to estimate average height in each of the five quadrats then averaging to determine height for the plot.

2.5 Data Analyses and Interpretation

Residuals were tested for normality using the Shapiro-Wilk test (Schlotzhauer and Littell 1997) and raw data were tested for homogeneity of variance using Bartlett's test (Steel et al. 1997). For the plant tissue chemistry data, a two way analysis of variance (ANOVA) was conducted on each site at each year and each depth. If treatment effect was significant the following planned orthogonal contrasts and polynomials were conducted: 1) Do increasing rates of biosolids show a linear effect, 2) Do increasing rates of biosolids show a quadratic effect, 3) Is the control treatment different from the inorganic fertilizer treatment, and 4) Is the inorganic fertilizer treatment different from the biosolids 150 Mg ha^{-1} treatment? At both sites in 1999 and at the sand site in 2000, plant growth was so limited and samples so small on the control and fertilizer amended plots that chemical analyses could not be conducted. In these cases statistical analyses were run with these two treatments removed from the design and the planned orthogonal contrasts and polynomials were corrected to answer the following questions: 1) Do increasing rates of biosolids show a linear effect and 2) Do increasing rates of biosolids show a quadratic effect? Year effects were studied by using a split-plot design with treatment as the main plot and year as the subplot. As baseline sampling confirmed sites were significantly different for the majority of the soil variables, a nested split-plot design with treatment as the main plot, year as the subplot and block nested within location was used to determine if a treatment by location interaction was occurring. All statistical analyses were conducted using the Proc Mixed with random command in SAS (SAS Institute, version 8).

Plant species composition data such as cover and frequency did not meet the assumptions required for parametric testing and therefore were analyzed using a nonparametric Friedman's 2-way ANOVA (Siegel and Castellan 1988).

Data that were significantly different but showed no biological significance are not reported (for statistical design/program used and complete tables refer to Appendices B and E). Results were considered significant at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Plant Yield and Species Composition

Increasing levels of biosolid amendment resulted in an increase in plant yield at both sites (Table 4.3). There was a significant site effect with the silt loam site having much higher overall yields and showing a quadratic response to increasing biosolids rates while the sand site had a lower but linear yield response. As discussed in Chapters II and III the silt loam site had fewer limitations to plant growth as it had a higher CEC, higher soil moisture and higher overall nutrient availability vs the sand site. At the sand site there was little to no growth on both control and inorganic fertilizer amended treatments while more growth was present on all applied biosolid treatments. Therefore, the addition of biosolids is more important in ameliorating site limitations such as limited soil organic matter and CEC then just the addition of nutrients. This increase in yield with biosolids has been noted in most studies using biosolids for land reclamation due to the extreme limitations of the sites prior to amendment addition (Norland and Veith 1995, Sopper 1993). Berti and Jacobs (1996) found yield reductions in some crops when biosolids with high metal loading rates were applied. In this study the growth response increased from the first to the second season which may be due to a variety of factors such as a wetter than average growing season in 2000 (Table 4.1) and also the fact that vegetation was seeded in June of 1999 while it had the full growing season to respond in 2000. Broersma et al. (1989) found that on agricultural soils in the central interior of BC a typical yield for a grass legume mixture with no fertilizer ranged from 4,000 to 6,000 kg ha^{-1} while a mixture with adequate fertilizer would yield 6,000 to 10,000 kg ha^{-1}. The study sites at HVC are at higher elevation and have a shorter growing season so expected yields on agricultural soils would be lower (estimated range of 3,000 to 5,000 kg ha^{-1}). By the second season yield at the silt loam site on the biosolids amended plots was nearing this range but yield at the sand site remained extremely low (Table 4.3).

Of the six species seeded Russian wild rye had poor establishment and/or growth response (Table 4.4). This species was seeded at a rate to produce approximately 15% cover (Table 4.2) but remained well below this level at both sites. Russian wild rye did not establish and later germination tests in a growth chamber resulted in an average germination of only 3% indicating that the seed was of poor quality. Russian wild rye has done well on sand dune sites although it is deemed to be a slow starter and has been unsuccessful in several other reclamation studies in Canada (Hardy BBT Limited 1989).

At the sand site, the plant community was dominated by alfalfa with lower amounts of pubescent wheatgrass, while all other species had < 2% cover each (Table 4.4). Bare ground decreased with increasing biosolids but even at the highest application rate remained above 60%. Plant cover is important as it helps protect the soil surface and decreases runoff (Gutierrez and Hernandez 1996). There is uncertainty with the amount of cover needed to control runoff and erosion but in general greater than 50 to 70% is required (Gutierrez and Hernandez 1996). This means that the sand tailings are at high risk for wind and/or water erosion.

At the silt loam site by the end of the second growing, bare ground decreased to <3% with biosolids, even at the lowest rate of 50 Mg ha^{-1} (Table 4.4). Increasing biosolids led to higher cover of pubescent wheatgrass but decreasing orchard grass. Alfalfa and alsike clover were not significantly impacted by biosolids but alfalfa made up a large part of the plant community while alsike clover remained <8% cover. Creeping red fescue showed a treatment response but remained at <3%. The cover, frequency, height and yield data for the control and fertilizer treatments were similar, although not tested statistically due to lack of samples as a result of minimal growth on these treatment plots.

At the sand site total cover remained similar between the two growing seasons while at the silt loam site there was an increase in cover between years, especially for the lower rate biosolid treatments. Alfalfa and alsike clover cover and frequency decreased by 2000 indicating legumes had good initial establishment and growth but may have been out-competed by grasses during the second year. Average plant height increased with treatment at both sites but was more than double at the silt loam vs the sand site. Plant heights were 14 to 127 cm for the control and biosolids 250 Mg ha^{-1} treatment at the silt loam site and 3 to 55 cm for the control and biosolids 250 Mg ha^{-1} treatment at the sand site (Appendix E).

3.2 Plant Tissue Chemistry

3.2.1 Nitrogen

The element most often limiting in reclamation of disturbed land is N (Sopper 1993). Plant tissue N levels responded with a linear increase to increasing levels of biosolids except at the sand site in 1999 (Table 4.5). Nitrogen levels were higher in the first season of growth than the second and by 2000 the response to biosolids was small with low rates of biosolids (<100 Mg ha^{-1} biosolids). Biosolids at a rate of 150 Mg ha^{-1} increased plant tissue N concentration over that of an inorganic fertilizer. The fertilizer and control treatments were not different.

Increased plant tissue N content with increased biosolids was found in most studies (Sopper 1993, Harrison et al. 1991, Topper and Sabey 1986, Hinesly et al. 1982, Griebel et al. 1979). This resulting increase in N is one of the main reasons for the increased growth response with biosolids (Harrison et al. 1991). The higher concentrations in the first year are related to the large readily available N added via biosolids as available NO_3-N and ammonium (NH_4-N). Of concern is a high level of

NO_3-N in the forage, which may put cattle at risk of NO_3-N poisoning. Forage NO_3-N levels were not measured but as total N remained within the range for healthy plants (Table 4.6) nitrate poisoning is not considered a high risk. Cattle would not graze these sites until several years after plant establishment and by year two N in the forage had decreased. Sopper (1993) was unable to find a reported case of NO_3-N poisoning in his literature review. However, Joost et al. (1987) noted NO_3-N plant tissue concentrations considered toxic to ruminants for the first three years after sludge application when rates of up to 900 Mg ha^{-1} were applied.

3.2.2 Phosphorus

Plant tissue P increased with increasing biosolids (Table 4.7). Topper and Sabey (1986) and Hinesly et al. (1982) found similar increases in plant P. However, Griebel et al. (1979) found only a small response to P with increasing biosolids compost. All plant tissue contained P at a level considered normal for healthy plants (Table 4.6).

3.2.3 Potassium

Biosolid additions resulted in a treatment response for plant K concentration at the sand site in 1999 (Table 4.8). As levels of total K in the tailings were not impacted by biosolids addition and available K was only increased at the sand site the general lack of treatment response is not unexpected. Similar results were reported by Griebel et al. (1979) who found even with biosolid additions up to 224 Mg ha^{-1} plant tissue concentration of K did not change. Biosolids usually contain low levels of K (Griebel et al. 1979). The plant K treatment response at the sand site may have been due to the lower levels of K at this site. In 1999 even with the addition of up to 100 Mg ha^{-1} of biosolids K remained below normal plant concentrations. The low K in the control treatment at the sand site may be limiting to plant growth.

3.2.4 Other macronutrients

Calcium concentration in plant tissue showed a treatment response to increased biosolid additions but this response was not always linear. At the sand site, addition of biosolids at 150 Mg ha^{-1} resulted in the highest Ca while at the silt loam site the response was variable. Ca generally remained in or above the high end of the range considered normal in vegetation (Table 4.6 and 4.9). Due to the neutral pH at the study sites and the high Ca in the tailings material this element was expected to be more than sufficient for plant growth. Other studies have noted increases in Ca with increased biosolids addition (Hinesly et al. 1982, Griebel et al. 1979).

At higher pH, Mg is often not limiting (Roberts et al. 1988). A treatment response was noted with Mg but the increase was slight and in all cases Mg remained within the normal range for plants (Table 4.6 and 4.9). As with the other macronutrients, increases in plant Mg are common with increased biosolids (Sopper 1993, Hinesly et al. 1982, Griebel et al. 1979). The treatment response noted in our study was mainly linear but Mg levels decreased slightly from 1999 to 2000.

The impact of biosolids on plant S levels is not well documented in the literature. Our results indicate a limited treatment response to biosolids (Table 4.9) with increasing biosolids either having no impact or causing a slight decrease. As S remained within a normal range these changes were not deemed biologically significant. Sulfur levels in the tissue decreased from 1999 to 2000.

3.2.5 Micronutrients

Boron in the plant tissue did not increase with increasing biosolids but did increase with addition of B containing inorganic fertilizer (Appendix E). However, all values were below 100 ppm, which is the suggested tolerance level for agronomic crops (Sopper 1993).

Copper in plant tissue showed a variable response to biosolid with a linear decrease in Cu uptake on the sand site in 1999 and a quadratic effect on the silt loam site in 2000 (Table 4.10). Griebel et al. (1979) found no impact on Cu in plant tissue with increasing rates of biosolids compost and attributed this to the subsequent increase in soil pH. The soil analysis from these sites indicate similar trends with available Cu decreasing at the sand site in 1998 but showing a limited treatment response at the silt loam site and in other time periods. As these tailings materials and biosolids contain similar levels of Cu the impact of biosolids addition on plant Cu is expected to be small. Cu exceeded the normal levels found in vegetation (Table 4.6) although they remain below the suggested tolerance level for agronomic crops (Sopper 1993). Several other sources suggest levels as low as 25 to 40 ppm may be considered phytotoxic (Webber et al. 1984). In all cases the Cu in the forage remained below the maximum cattle tolerance level of 100 ppm (Logan and Chaney 1983).

Increasing biosolids decreased total Mo in the plant tissue for all years and at both sites (Table 4.11). The response was linear in 1999 at the silt loam site and in 2000 at the sand site. In 1999 at the sand site the response was quadratic and the impact leveled off at the biosolids application rate of 150 Mg ha^{-1}. The leveling off was more of a result of limitations in the equipment to read below 1 ppm Mo. The control and fertilizer treatments did not differ and were higher than the biosolid treatments. McBride et al. (2000) found biosolid addition increased Mo in plant tissue, especially the legumes. In their study biosolids were applied to pH neutral agricultural soils that did not contain significant Mo to start with. Harrison et al. (1991) noted that in some studies metal uptake was reduced and was attributed to organic matter in the biosolids acting to bind these elements. McBride et al. (2000) also found Mo is retained in soil organic matter and can have a long residual availability in biosolids amended soil. The decrease in Mo may also be due to a dilution effect of biosolids on tailings material as Mo in the tailings is higher than that of biosolids. Even with the reduction in Mo, in almost all cases with the plant tissue being greater than 10 ppm Mo was high enough to be considered a risk to ruminant animals (Table 4.6).

Both Mn and Zn showed a linear response to biosolids. There was no difference in Mn between control and fertilizer treatments or fertilizer and biosolids 150 Mg ha^{-1} treatments (Table 4.9). Rates greater than 150 Mg ha^{-1} of biosolids increased plant tissue Mn above that of fertilizer alone but resulted in values slightly above those considered normal for vegetation (Table 4.6). Zinc remained in the normal range (Table 4.6) and fertilizer addition did not differ from biosolids applied at 150 Mg ha^{-1} indicating biosolids increased Zn in the plant tissue but only at higher applications. Berti and Jacobs (1996) and Hinesly et al. (1982) both noted increases in these elements in plant tissue with addition of biosolids. Hinesly et al. (1982) did not see a linear response and found that when increasing application rates from 448 to 896 Mg ha^{-1} the concentration of the majority of trace elements did not double. At lower applications a more linear treatment response similar to that noted in our study was seen.

Cobalt in plant tissue was below equipment detection limits of 1 ppm. Iron did not vary with biosolids (Table 4.9) and all treatments remained within normal plant tissue ranges (Table 4.6).

3.2.6 Other elements

Arsenic, Cd and Cr in plant tissue were all below equipment detection limits and therefore no treatment response could be determined. Cadmium and Cr remained below 1 ppm (Table 4.9) falling within the normal range for plant tissue concentrations (Table 4.6). The equipment could only detect As above 5 ppm but levels that can be considered toxic to plants can occur as low as 3 ppm (Table 4.6). Since total As in the soil remained below 5 ppm (Chapter III) and concerns for grazing animals are only at values >50 ppm (Webber et al. 1984), this element likely poses little risk at these sites. Nickel and Pb both showed no response to treatment and remained close to the normal range for plant tissue (Table 4.6). Both elements slightly exceeded their normal plant tissue range but were well below levels considered toxic to plants or animals.

In other studies a general increase in most of these elements was noted. Hinesly et al. (1982) and Peterson et al. (1979) found an increase in Cd and Ni, and Joost et al. (1987) found increased Cd, Cr, Ni and Pb. Griebel et al. (1979) found decreased Ni in plant tissue with increasing biosolids but attributed this to increased pH.

3.3 Change in Element Concentrations Over Time

Nitrogen, K, Mg, S, B and Zn in plant tissue decreased from 1999 to 2000, remaining within the range for normal plant tissue. This trend has been found often in the literature, especially with a single biosolid application (Sopper 1993). This decrease is likely the result of a flush of available nutrients in the first year of growth after biosolids application which then decreases as soluble forms are leached, taken up by plants or bound to soil organic matter. As plant yield was higher in the second year, the decreased nutrients may be related to a dilution effect from the increase in overall dry matter. In this study Mo in plant tissue increased at the sand site from 1999 to 2000 with increasing biosolids resulting in low Mo in the first year of growth.

3.4 Fertilizer versus Biosolids Amendments

Fertilizer application did not increase total yield over that of the control treatment. Biosolids application at a rate of 150 Mg ha^{-1} was significantly higher than the fertilizer treatment alone. Due to very limited growth on the fertilizer plots the only year with sufficient vegetation for chemical analysis was 2000 and only at the silt loam site. These limited plant tissue data indicated chemical fertilizer had little effect on most elements but increased B beyond that of biosolids. Topper and Sabey (1986) compared biosolids to different inorganic fertilizer application rates and found superior growth with the organic amendment. They attributed this not to nutrient addition alone but to improved soil physical conditions and possibly increased biological and microbial activity.

3.5 Implications for Livestock Grazing

All elements, with the exception of Mo, remained at levels below maximum levels for cattle tolerance (Table 4.6). Harrison et al. (1991) in their literature review stated that toxicity of trace metals from biosolids application has never resulted in direct injury to either plants or animals. Sopper (1993) reported that although metals may increase in plants grown on biosolids amended sites in most cases these increases are not sufficient to be a concern for animal health. In studies involving grazing cattle on land treated with anaerobically digested biosolids, Fitzgerald (1979, 1982) found no indications of disease or transmission of pathogens. Increases in Cd and Pb, however, were found in the kidney and liver of the cattle but remained below levels considered harmful for human consumption (Fitzgerald 1982).

The only element of concern in this study was Mo which is higher in the unamended tailings and so is not directly a result of biosolids addition. Ruminant animals grazing forage with high Mo may be at risk of molybdenosis, a secondary Cu deficiency that occurs in animals consuming feed containing high Mo (Ward 1994). Ruminants are susceptible to this disease with cattle having the lowest tolerance (Ward 1994). Symptoms include severe diarrhea, weight loss, colour loss in hair, lameness with a characteristic stiff gait, and sometimes death (Ward 1994, NRC 1996). Researchers have shown that 10 ppm or less of Mo in forage can result in molybdenosis (Suttle 1991, Leech and Thornton 1987) and a Cu:Mo ratio of 2:1 in plant tissue should be maintained to limit risk to ruminant animals (Miltimore and Mason 1971, Fletcher and Brink 1969). Karn and Hofmann (1990) grazed cattle on reclaimed mined land with forage containing elevated Mo and noted increased Mo in the liver but no symptoms of a Cu deficiency or molybdenosis. Past studies at HVC on reclaimed tailings sites have shown forage with up to 34 ppm Mo and an average Cu:Mo ratio of 0.47:1 did not result in any symptoms of molybdenosis although Mo concentrations in the serum and liver of animals increased (Gardner et al. 2003). Continuing studies at HVC on vegetation containing much higher levels of Mo (95 to 460 ppm range) resulted in some animals exhibiting symptoms of molybdenosis although these symptoms were alleviated by supplementing with additional Cu (Majak et al. 2004). At the silt loam site plant tissue in the control had a Cu: Mo ratio of 0.26:1 while at a biosolids application rate of 250 Mg ha^{-1} the Cu:Mo ratio increased to 1.3:1.

Even with biosolid additions at the highest rates plant cover and yield was limiting at the sand site. Thus cattle grazing should be excluded from these reclaimed sites for the first few years after biosolids addition to allow the plant community to establish and further ameliorate the harsh soil conditions. Stocking rates should be conservative as tailings material is sensitive to disturbance and trailing (Gizikoff 2003) as it has little or no structure.

Current concerns with domestic animal grazing on biosolids amended sites focus on dioxin levels and potential accumulation in cattle ingesting forage from amended sites. Dioxin levels and uptake by cattle grazing areas treated with biosolids are currently being investigated (Broersma 2004, personal communication).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

- A one time incorporation of biosolids at 50 to 250 Mg ha^{-1} had beneficial impacts on vegetation yield, composition and chemistry.
- The addition of biosolids increased yield at both sites.
- All elements except Mo and Cu remained in the range considered normal for vegetation. The elevated Cu levels were below the suggested tolerance level for agronomic crops and for cattle. Molybdenum levels exceeded those considered safe for cattle consumption but addition of biosolids lowered these levels and increased the Cu:Mo ratio.
- Application of inorganic fertilizer did not increase yield over that of the control for most elements in the vegetation. Boron was the exception; it remained similar between the control and the fertilizer treatments. These results indicate that the increased yield and overall site productivity were more related to the alteration of other soil chemical and physical parameters than just the nutrient level alone.
- Elements in the vegetation showed a response to time with concentrations of K, Mg, S, B and Zn decreasing over the two years.

4.2 Management Recommendations

- An organic amendment, such as biosolids, is required for reclamation and revegetation of these sites as inorganic chemical nutrient addition alone shows no response in yields and is not considered sufficient to ameliorate the poor growing conditions prevalent at these sites.

- Biosolid addition raised the overall Cu:Mo ratio, reducing the risk of molybdenosis. Previous studies at HVC indicate these levels of Mo pose minimal risk but caution is recommended in grazing animals on these sites and that a Cu supplement be made available.
- At fine textured sites low levels of biosolids application (50 Mg ha^{-1}) may be sufficient to increase cover to over 80% and reduce erosion concerns. At coarse textured tailings sites, application rates higher than 250 Mg ha^{-1} are recommended to help ameliorate poor site conditions or other organic amendments with more of an impact on water holding capacity may be required.

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Table 4.1. Climate information at the tailings sites over the three years from the Lornex weather station (C.E. Jones and Associates 1999, 2000 and 2001).

Variable	1998	1999	2000
Snowfall from Nov 1-March 31 (cm)	88	157	77
Rainfall from Nov 1-March 31 (mm)	77	59	25
Precipitation from April-Oct (mm)	182	172	386
Temperature range from April-Oct (°C)	-6.5 to 33	-11 to 28	-8.5 to 28
Growing degree days	1509	975	1037
Frost free period (days)	173	136	169
Monthly mean annual minimum temperature (°C)	-5 (Jan)	-5 (Dec)	-5 (Dec)
Monthly mean annual maximum temperature (°C)	17.5 (Aug)	15 (Aug)	15 (July)

Table 4.2. Information used in the calculation of the seed mix and final kg ha^{-1} of seed applied.

Species	Desired Final Cover (%)	Emergence and survivability (%)	Estimated Germination (%)	Seeding Rate (kg ha^{-1})
Pubescent wheatgrass	20	80	92	12.4
Orchard grass	20	52	94	2.8
Creeping red fescue	15	80	93	1.5
Russian wild ryegrass	15	80	89	5.5
Alfalfa	15	33	80	12.9
Alsike clover	15	52	85	2.2

Table 4.3. Total vegetation yield (kg ha^{-1}).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	2	3	88	174
	Fertilizer	*26	20	*172	163
	Biosolids 50	310	161	1780	853
	Biosolids 100	433	197	2041	734
	Biosolids 150	*475	197	*1898	1324
	Biosolids 200	375	93	2248	1408
	Biosolids 250	435	193	2269	1296
Treatment p value		0.0001 quadratic		0.0001 quadratic	
Sand Site	Control	0	-	0	-
	Fertilizer	*0	-	*2	5
	Biosolids 50	26	18	108	108
	Biosolids 100	29	24	192	104
	Biosolids 150	*65	28	*340	169
	Biosolids 200	71	42	310	166
	Biosolids 250	91	44	453	125
Treatment p value		0.0001 linear		0.0001 linear	

N = 8 for each year

SD = standard deviation

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment; no significant difference noted for orthogonal contrast control vs fertilizer treatment

Table 4.4. Plant tissue composition by % cover and bare ground for 2000.

Treatment	PWG	SD	OG	SD	CRF	SD	ALF	SD	ALS	SD	Other	SD	Bare	SD
Silt Loam Site														
Control	0	0	3.4	4.4	2.2	1.8	5.2	12.1	0.2	0.4	1.1	2.8	88.0	17.1
Fertilizer	0.3	0.3	3.3	2.7	2.3	1.8	11.1	14.8	0.3	0.6	0.5	1.1	82.3	12.8
Biosolids 50	18.8	13.2	54.4	31.6	1.9	2.2	16.9	20.6	7.6	10.2	0.1	0.2	0.4	0.7
Biosolids 100	28.8	16.1	49.1	27.1	0.5	1.5	14.5	20.0	6.0	7.7	0.8	1.4	0.3	0.8
Biosolids 150	31.2	16.3	33.5	32.0	0	0	29.8	33.4	5.5	8.9	0.1	0.1	0	0
Biosolids 200	34.5	10.2	34.0	27.2	0.1	0.4	25.3	30.0	2.3	3.0	1.5	3.5	2.3	6.4
Biosolids 250	41.7	23.1	21.3	19.6	0	0	29.8	34.8	4.0	7.2	2.9	6.9	0.4	1.1
p value	0.0001		0.0001		0.0001		0.2547		0.2843		0.9386		0.0001	
Sand Site														
Control	0.1	0.1	0	0	0.2	0.3	0	0.1	0	0	0	0	99.7	0.3
Fertilizer	0.3	0.3	0.2	0.4	0.3	0.4	0.3	0.6	0	0	0	0	98.9	1.4
Biosolids 50	5.1	2.8	0.7	1.4	0.9	1.7	4.1	4.6	0	0	0.1	0.1	89.3	8.2
Biosolids 100	5.3	3.1	0.2	0.5	0.3	0.7	8.7	4.7	0.1	0.1	0	0	85.5	5.3
Biosolids 150	6.1	4.1	0.2	0.4	1.8	1.9	20.4	11.7	0.4	0.7	0	0	71.2	12.8
Biosolids 200	8.3	6.5	0.4	0.8	0.2	0.4	16.5	17.6	0	0	0.4	0.8	74.3	17.2
Biosolids 250	9.3	3.2	0.6	0.9	1.5	2.7	25.0	14.2	0.1	0.4	0.5	0.8	63.0	14.7
p value	0.0001		0.7004		0.2610		0.0001		0.2696		0.0914		0.0001	

N = 8 for each year

SD = standard deviation

PWG- pubescent wheatgrass, OG - orchard grass, CRF - creeping red fescue, ALF - alfalfa, ALS -alsike clover, Other - species other than those seeded, Bare - bare ground (Russian wild rye failed to establish)

Table 4.5. Plant tissue total nitrogen content (%).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	-	-	1.67	0.56
	Fertilizer	-	-	*1.96	0.61
	Biosolids 50	3.98	0.40	1.63	0.24
	Biosolids 100	4.35	0.41	1.89	0.35
	Biosolids 150	4.31	0.44	*2.46	0.34
	Biosolids 200	4.53	0.40	2.17	0.25
	Biosolids 250	4.66	0.33	2.61	0.37
Treatment p value		0.0001 linear		0.0001 linear	
Sand Site	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	4.09	0.50	1.83	0.40
	Biosolids 100	4.10	0.31	2.06	0.41
	Biosolids 150	4.09	0.20	2.70	0.26
	Biosolids 200	4.11	0.48	2.68	0.22
	Biosolids 250	3.90	0.29	2.88	0.21
Treatment p value		0.7609		0.0001 linear	

N = 8 for each year

SD = standard deviation

Lines without values were not analyzed for due to insufficient sample size

* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment

Table 4.6. Normal and toxic plant and animal concentration levels of various elements.

	Plant Concentrations		Beef Cattle Guidelines*	
Element	Normal	Tolerance**	Required	Maximum Tolerable Concentration
Macronutrients				
N (%)	1- 5	-	-	-
P (%)	0.1 - 0.4	-	-	-
K (%)	1 - 5	-	0.6	3
Ca (%)	0.2 - 1.0	-	-	-
Mg (%)	0.1 - 0.4	-	0.1	0.4
S (%)	0.1 - 0.4	-	0.15	0.4
Micronutrients				
B (ppm)	7 - 75	100	-	150
Co (ppm)	0.01 - 0.3	5	0.1	100
Cu (ppm)	3 - 20	150	10	100
Fe (ppm)	30 - 300	750	50	1000
Mn (ppm)	15 - 150	300	20	1000
Mo (ppm)	0.1 - 3.0	100	-	5 to 10
Zn (ppm)	15 - 150	300	30	500
Other Elements				
As (ppm)	0.01 - 1	3 - 100	-	50
Cd (ppm)	0.1 - 1	3	-	0.5
Cr (ppm)	0.1 - 1	2	-	3000
Ni (ppm)	0.1 - 5	50	-	50
Pb (ppm)	2 - 5	10	-	30

Sources: Macronutrient information from Tisdale et al. (1985) and micronutrient and other element information from Webber et al. (1984), Sopper (1993) and Logan and Chaney (1983); beef cattle guidelines for macro and micronutrients from NRC (1996) and for other elements from Webber et al. (1984).

* Beef cattle guidelines for growing animals.

** Suggested tolerance level for agronomic crops or phytotoxic level.

Table 4.7. Plant tissue total phosphorus content (%).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	-	-	0.19	0.06
	Fertilizer	-	-	*0.24	0.07
	Biosolids 50	0.29	0.05	0.23	0.05
	Biosolids 100	0.33	0.09	0.24	0.06
	Biosolids 150	0.34	0.06	*0.33	0.06
	Biosolids 200	0.39	0.07	0.30	0.03
	Biosolids 250	0.43	0.08	0.37	0.05
Treatment p value		0.0001		0.0001	
		linear		linear	
Sand Site	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	0.31	0.06	0.30	0.08
	Biosolids 100	0.34	0.05	0.40	0.08
	Biosolids 150	0.36	0.05	0.43	0.07
	Biosolids 200	0.39	0.06	0.40	0.07
	Biosolids 250	0.44	0.07	0.44	0.04
Treatment p value		0.0015		0.0021	
		linear		quadratic	

N = 8 for each year
SD = standard deviation
Lines without values were not analyzed for due to insufficient sample size
* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment

Table 4.8. Plant tissue total potassium content (%).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	-	-	1.41	0.35
	Fertilizer	-	-	1.77	0.35
	Biosolids 50	3.42	0.85	1.69	0.66
	Biosolids 100	3.37	0.95	1.61	0.67
	Biosolids 150	3.26	0.93	2.07	0.81
	Biosolids 200	3.21	0.90	1.71	0.59
	Biosolids 250	3.29	0.76	1.96	0.74
Treatment p value		0.7682		0.2157	
Sand Site	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	0.80	0.30	1.92	0.57
	Biosolids 100	0.95	0.33	2.02	0.56
	Biosolids 150	1.10	0.13	1.91	0.88
	Biosolids 200	1.53	0.26	1.99	0.61
	Biosolids 250	2.12	0.44	1.98	0.96
Treatment p value		0.0001 quadratic		0.9756	

N = 8 for each year
SD = standard deviation
Lines without values were not analyzed for due to insufficient sample size

Table 4.9. Mean (1999 and 2000 combined) plant tissue concentration of macronutrients, micronutrients and other elements.

Element	Silt Loam Site			Sand Site	
	Control*	Fertilizer*	Biosolids 150	Control**	Biosolids 150
Macronutrients					
N (%)	1.67	1.96	3.39	3.53	3.40
P (%)	0.19	0.24	0.34	-	0.40
K (%)	1.41	1.77	2.67	-	1.50
Ca (%)	1.10	1.58	1.46	-	3.25
Mg (%)	0.19	0.24	0.30	-	0.41
S (%)	0.25	0.28	0.30	-	0.31
Micronutrients					
B (ppm)	27.9	59.5	46.3	-	67.9
Co (ppm)	<1.0	<1.0	<1.0	-	<1.0
Cu (ppm)	29.0	36.3	25.9	-	44.6
Fe (ppm)	177.0	200.0	110.0	-	150.0
Mn (ppm)	126.4	154.4	162.1	-	246.6
Mo (ppm)	111.9	108.4	28.9	-	9.0
Zn (ppm)	36.7	53.8	65.8	-	111.5
Other Elements					
As (ppm)	<5.0	<5.0	<5.0	-	<5.0
Cd (ppm)	<1.0	<1.0	<1.0	-	<1.0
Cr (ppm)	<1.0	<1.0	<1.0	-	<1.0
Ni (ppm)	5.9	2.5	1.3	-	2.6
Pb (ppm)	2.0	2.5	2.1	-	2.1

* Value from 2000 only

** Value determined from one sample only

Table 4.10. Plant tissue total copper content (ppm).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	-	-	29.0	11.6
	Fertilizer	-	-	*36.3	9.4
	Biosolids 50	27.6	5.9	20.0	6.4
	Biosolids 100	35.3	25.3	20.5	6.9
	Biosolids 150	25.0	6.2	*26.8	6.7
	Biosolids 200	26.1	6.0	23.8	7.8
	Biosolids 250	27.4	10.2	29.1	8.7
Treatment p value		0.5453		0.0032 quadratic	
Sand Site	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	64.8	32.8	31.0	17.0
	Biosolids 100	74.3	33.5	37.4	17.4
	Biosolids 150	53.1	19.5	36.1	10.7
	Biosolids 200	55.9	23.4	37.4	17.7
	Biosolids 250	34.1	14.8	33.6	8.2
Treatment p value		0.0447 linear		0.8901	

N = 8 for each year
SD = standard deviation
Lines without values were not analyzed for due to insufficient sample size
* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment

Table 4.11. Plant tissue total molybdenum content (ppm).

Site	Treatment	1999	SD	2000	SD
Silt Loam Site	Control	-	-	111.9	42.4
	Fertilizer	-	-	*108.4	33.5
	Biosolids 50	53.9	22.3	48.9	11.3
	Biosolids 100	56.1	66.9	37.8	28.6
	Biosolids 150	22.1	7.9	*35.6	22.7
	Biosolids 200	13.5	3.7	23.3	7.3
	Biosolids 250	12.9	3.9	22.0	6.9
Treatment p value		0.0141 linear		0.0001 quadratic	
Sand Site	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	6.0	3.2	34.4	18.2
	Biosolids 100	2.3	1.0	21.6	13.6
	Biosolids 150	1.1	0.4	16.9	9.2
	Biosolids 200	<1.0	0.0	17.4	14.5
	Biosolids 250	<1.0	0.0	8.4	4.5
Treatment p value		0.0001 quadratic		0.0043 linear	

N = 8 for each year
SD = standard deviation
Lines without values were not analyzed for due to insufficient sample size
* denotes significant difference ($p<0.05$) for orthogonal contrast fertilizer vs biosolids 150 treatment

V. SYNTHESIS

1. INTRODUCTION

Application of biosolids amendments resulted in positive changes to soil physical, chemical and microbiological properties in addition to its influence on plant yield, composition and element uptake. Biosolids addition decreased bulk density, decreased penetration resistance in the upper 12 cm of tailings, increased gravimetric water retention at field capacity and wilting point, and decreased volumetric water holding capacity (WHC) (silt loam site only). The microbial community was significantly altered by biosolid additions with the number of total aerobes, total anaerobes, iron reducers, sulfate reducers and denitrifiers all increasing compared to the fertilizer addition or no amendment. Soil organic matter, electrical conductivity (EC), cation exchange capacity, total nitrogen(N), carbon (C), phosphorus (P), sulfur (S), magnesium (Mg), iron (Fe), zinc (Zn), nickel (Ni) and lead (Pb) and available nitrate (NO_3-N), ammonium (NH_4-N), P, Fe, manganese (Mn) and Zn increased with biosolids. Molybdenum (Mo) decreased with increasing amounts of biosolids. Plant yield increased with increasing levels of biosolids while bare ground decreased. Biosolids addition also increased elemental uptake of N, P, calcium (Ca), Mg, Mn and Zn and decreased Mo, resulting in a higher copper (Cu):Mo ratio. The inorganic fertilizer treatment had similar results to the control. There were changes over time but in general treatment response remained similar across the three years. The treatment response was mainly in the upper 15 cm (depth of incorporation) of the tailings and small impacts were seen at 15 to 30 and 30 to 45 cm depths.

2. SITE RESPONSE TO TREATMENT

One of the objectives of this study was to compare treatment response between two climatically similar sites with different soil textures. For most parameters tested, there was a significant difference between sites but the response to treatment was generally similar. For example, the increase in yield was much higher at the silt loam site than the sand site, but at both sites increasing rates of biosolids resulted in higher plant yields. Volumetric WHC was one of the main exceptions, decreasing with increasing biosolids at the silt loam site, with no response at the sandy site. These results indicate that although soil texture has a significant impact on soil physical, chemical, microbiological and vegetation properties of a site, the directional response to biosolid additions will be similar. However, the level of response can vary widely between sites, making it hard to determine the best application rates across different tailings textural materials.

3. ECOLOGICAL PROCESSES

Another objective of this study was to discuss the interrelationships of soil physical, chemical and microbial and plant yield, composition and element uptake within the context of the soil-plant-water-animal system. Key ecosystem processes include water cycling, energy flow and nutrient storage and cycling. If a reclaimed site is to be sustainable in the long-term these processes must be established and maintained. However, it is very difficult to directly measure ecological processes as they are interrelated and extremely complex; so indicators of certain biological and physical attributes can be used (Pellant et al. 2000). For example, a rangeland health method uses 17 indicators to measure degree to which the integrity of the soil, vegetation, water and air, as well as ecological processes of the rangeland ecosystem are balanced and sustained (Pellant et al. 2000). The theory behind the rangeland health concept can also be applied to land reclamation and the various parameters measured in this study can be indicators for water cycling, nutrient cycling and energy flow (Table 5.1).

This concept makes it is easier to look at interrelationships and address effectiveness of different amendments in establishing ecosystem processes. The results of this study indicate that a one time inorganic fertilizer amendment did little to speed soil development or to create a more favourable growth environment by altering many of the parameters listed in table 5.1. The addition of biosolids led to an improvement in a majority of parameters compared to the unamended control. The increase in organic matter appeared to be critical in increasing the activity of the microbial community and nutrient availability and improving water retention. The resulting increase in plant cover will further help ameliorate site challenges by increasing organic matter content. One concern for the higher yielding sites is that initial decomposition rates may be too low to deal with the large accumulations of vegetation so removal of some biomass by grazing or mowing is recommended. Overall, biosolid additions are helping re-establish ecological processes and are increasing site sustainability over the use of inorganic fertilizer or implementation of no amendments to these tailings areas.

4. MANAGEMENT IMPLICATIONS

This bigger picture is important in summarizing some of the main management implications. An often asked question is what rate of biosolids application is the most effective, both biological and economically? The answer is site specific as shown by differences just between the two sites in this study. The type of spoil material, the surrounding climate and the quality of biosolids used will all impact what application rate should be used. In general, on areas with fairly severe limitations to plant growth the highest rate is the most beneficial in ameliorating site challenges and increasing plant growth. Metal movement at higher biosolids application rates was not a problem but should be considered as this study was conducted in a fairly low precipitation environment.

Another key question is how do these reclamation practices impact human safety? The application of biosolids at reclamation rates of up to 250 Mg ha^{-1} have a small impact on safety to animals grazing the area and therefore to humans consuming these animals. Levels of all elements measured, except Mo and Cu, remained within the range considered normal for vegetation and, since deemed safe for cattle consumption, pose little or no threat to human health. Movement of these elements in the soil profile was also small and therefore entry into water bodies is not considered a large risk. The main concern is the level of Mo in plant tissue, even though biosolids helped lower this level. This is a concern for ruminant animals grazing this vegetation but is considered a small concern for humans.

Can the sites be used safely for an end land use of grazing by wildlife and domestic livestock? This question is more difficult to answer. The vegetation or forage that is produced is of better quality for animal consumption as it had higher protein and nutrients than unamended vegetation but there are associated risks with grazing these areas due to high Mo. Past studies conducted at Highland Valley Copper (HVC) on reclaimed tailings with similar and higher Mo levels and lower Cu:Mo ratios have demonstrated that with proper management these sites can be safely grazed. If used for grazing these sites will need to be closely monitored and additional supplements containing Cu should be made available. These areas should be used later in the season when forage is more mature and Mo levels have decreased. These management practices can be put in place for domestic livestock but it will be difficult to manage other ruminant animals such as deer and moose that frequent these areas. Large ungulates have the ability to move on and off the site and preliminary observations on their movement indicated that they only spend certain parts of the year on reclaimed sites and move between the nearby forested areas and open tailings sites. The limited amount of forage available at the sand site is also of concern. On these coarse textured tailings where plant growth is limited even with high rates of biosolids, domestic livestock grazing should not be part of the end land use plan.

A final management question is whether the reclamation tools assessed in this study lead to the development of a self-sustaining site. This question is one that is difficult to answer without long-term data collection. Three years of research makes it hard to predict if a community will function in the long-term without any additional inputs. The results indicate that a one time application of inorganic fertilizer is not sufficient for even short-term reclamation goals. However, incorporation of biosolids, especially at higher rates helps increase soil development and there is strong evidence of increased nutrient cycling, energy flow and improved water cycling. Improvement in theses key ecological processes indicate the system is recovering and longer term site sustainability may be achievable.

5. ADVANCEMENTS TO THE SCIENTIFIC KNOWLEDGE BASE

This study has helped to advance the scientific knowledge base by filling some of the gaps in the current research. The results have helped expand information in biosolid additions on different types of reclamation tailings materials and their impacts on microbialogical communities. Studying each parameter separately has helped increase the knowledge base for soil physical, microbiological, and chemical properties as well as plant yield, composition and element uptake. Using these individual parameters as indicators of ecological processes has helped address the interrelationships among the soil-plant-water-animal systems and discuss the effectiveness of biosolids as a reclamation tool. Most studies using biosolids in reclamation have been on acidic tailings. This study has provided findings for alkaline materials. Limited information on the macronutrient S was previously documented. The impact of tailings texture on plant available WHC produced unexpected results. Of particular importance is the information gained on the impact of biosolids on high Cu and Mo tailings and the consequences on possible end land use.

6. REFERENCES

Pellant, M., Pyke, D., Shaver, P. and Herrick, J. 2000. Interpreting indicators of rangeland health, version 3. United States Department of Interior, Bureau of Land Management, National Science and Technology Center, Information and Communications Group. Denver, Colorado. 111 pp.

Table 5.1 Study parameters used as indicators for ecological processes.

Nutrient Cycling	Energy Flow	Water Cycling
Soil nutrient levels	Vegetation production	Bare ground
Plant nutrient levels	Vegetation composition	Compaction
Vegetation production	Microbial community	Water retention
Microbial community	Soil organic matter	Water holding capacity
Soil organic matter	Penetration resistance	Soil organic matter
Cation exchange capacity	Compaction	Penetration resistance
pH		

APPENDIX A

Additional Study Site Information

1. Background

Highland Valley Copper (HVC) is considered the largest copper (Cu) mine in Canada and one of the largest tonnage operations globally (Teck Cominco Ltd. 2004). In 2003, 67,494,000 tonnes of ore with an average Cu grade of 0.393% was mined producing 170,4000 tonnes of Cu and 7.3 million pounds of molybdenum (Mo) (Teck Cominco Ltd. 2004).

Mining has taken place in the Highland Valley area since 1954 (Freberg and Gould Gizikoff 1999). Highland Valley Copper consists of four mining properties amalgamated under one operation: Lornex, Valley, Bethlehem and Highmont. The Bethlehem operation began in 1962, Lornex in 1972, Highmont in 1982 and Valley in 1983 (Jones 2001). In 1986 Bethlehem, Lornex and Valley were joined together to form HVC and in 1988 Highmont also joined. Some early reclamation started in the 1970s and 1980s but the bulk of reclamation has taken place since 1990 (Jones 2001).

2. Site Information

This study was conducted at two different tailings sites on the HVC mine, Trojan, a sand site, and Bethlehem, a silt loam site. The tailings materials may be arranged in distinct layers due to the method of deposit and the variability that occurs in crushing the sediment. The tailings material has an amorphous structure and the organic matter content and cation exchange capacity (CEC) are low. A major site concern is erosion from wind and water due to lack of organic matter and soil structure. The soils are alkaline with a pH of approximately 7.0 to 8.0.

Even though the pH is currently alkaline, the soil weathering theory, as well as some studies conducted on these tailings materials in the laboratory, suggests that over time the pH of these tailings will decrease (Hackinen 1986). This occurs as alkali and alkaline earth elements such as calcium (Ca), sodium (Na) and potassium (K) are leached from the tailings by precipitation (Hackinen 1986). A previous three year study conducted on tailings at the HVC mine found soil pH highly variable and no reduction in pH was noted over this time span (HVC 1994). It is believed that the natural leaching of Ca and other alkaline elements from these sites will take a considerable amount of time and ongoing monitoring is now continuing every four years (HVC 1994).

The Bethlehem and Trojan tailings sites are both found in the upper elevation ranges of the Interior Douglas-fir (IDF) zone. The predisturbance vegetation on this site consists of species found in the IDF dry mild zone (IDFdm): yarrow (*Achillea millefolium* L.), kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.), northwestern sedge (*Carex concinnoides* Mack.), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco.), pinegrass (*Calamagrostis rubescens* Buckl.), saskatoon (*Amelanchier alnifolia* (Nutt.) Nutt. *ex* M. Roemer), showy aster (*Aster conspicuous* Lindl.), *Cladonia* P. Browne spp., *Peltigera* spp., red-stemmed feather moss (*Pleurozium schreberi* (Brid.) Mitt.), soopolallie (*Sheperdia Canadensis* (L.) Nutt.), birch-leaved spirea (*Spiraea betulifolia* Pall.), falsebox (*Paxistima myrsinites* (Pursh) Raf.), twinflower (*Linnaea borealis* L.), lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.), common juniper (*Juniperus communis* L.) and step moss (*Hylocomium splendens* (Hedw.) B.S.G.) (Hope et al. 1991).

3. References

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APPENDIX B
Statistical Design And SAS Programs Used

Statistical Design and SAS Program Used For Parametric Data

Part 1 – Analysis of variance (ANOVA) on randomized complete block design and preplanned orthogonal contrasts

Model $Y_{ij} = Y_{..} + T_i + B_j + e_{ij}$

Source of Variation Table

Block	r-1	SSb/df	MSb/MSe
Treatment	n-1	SSt/df	MSt/MSe
Error (B*T)	(r-1)(n-1)	SSe/df	
Total	(n*r)-1		

SS = sum of squares
Df = degrees of freedom
MS = mean square

Orthogonal Contrasts

	C	F	B50	B100	B150	B200	B250	Sum
Linear	-5	0	-3	-1	1	3	5	0
Quadratic	5	0	-1	-4	-4	-1	5	0
Control vs fertilizer	-1	1	0	0	0	0	0	0
Fertilizer vs biosolids 150 Mg ha^{-1}	0	-1	0	0	1	0	0	0

C = control, F = fertilizer, B = biosolids in Mg ha^{-1}

Part 1 - SAS Program

```
Proc sort data = input;
        By location year depth;
Proc mixed data = input;
        By location year depth;
        Class block trtid;
        Model var = trtid/ outp=onewaye;
        Random block;
        Lsmeans trtid;
Contrast 'linear rate' trtid -5 0 -3 -1 1 3 5;
Contrast 'quadratic rate' trtid 5 0 -1 -4 -4 -1 5;
Contrast 'control vs fertilizer' trtid -1 1 0 0 0 0 0;
Contrast 'fertilizer vs B150' trtid 0 -1 0 0 1 0 0;
Run;
```

Part 2 - Year effects; split-plot design with treatment as main plot and year as subplot (Using univariate approach so years as a random variable tested for circularity first using sphericity test)

Source of Variation Table

Block	a-1	SSb/df	MSb/MSe1
Treatment	b-1	SSt/df	MSt/MSe1
Block*trtid (error 1)	(a-1)(b-1)	SSe1/df	
Year	c-1	SSy/df	MSy/MSe2
Trtid*year	(b-1)(c-1)	SSty/df	MSty/MSe2
Block*trtid*year (error 2)	b(a-1)(c-1)	SSe2/df	
Total	abc-1		

Part 2 - SAS Program

```
Proc sort;
        By location depth;
Proc mixed data = input;
        By location depth;
        Class block trtid year;
        Model var = trtid | year/ddfm=satterth;
        Random block block*trtid;
        Lsmeans trtid year trtid*year;
Run;
```

Part 3 - Location; nested split-plot design with treatment as main plot, year as subplot and block nested within location

(Sites were selected because of differences; this test was run only to see if the treatment responds differently depending on location or testing for a treatment by location interaction)

Source of Variation Table

Location	r-1	SSl/df	MSl/MSe1
Blocks within location (error 1)	r(a-1)	SSe1/df	
Trtid	b-1	SSt/df	MSt/MSe2
Loc*trtid	(r-1)(b-1)	SSlt/df	MSlt/MSe2
Block*trtid*location (error 2)	r(a-1)(b-1)	SSe2/df	
Year	c-1	SSy/df	MSy/MSe3
Year*trtid	(c-1)(b-1)	SSyt/df	MSyt/MSe3
Year*location	(c-1)(r-1)	SSyl/df	MSyl/MSe3
Year*location*trtid	(c-1)(r-1)(b-1)	SSylt/df	MSylt/MSe3
Block*trtid*year*location (error 3)	ra(b-1)(c-1)	SSe3/df	
Total	rabc-1		

Part 3 - SAS Program

```
Proc sort;
        By depth;
Proc mixed data = input;
        By depth;
        Class block location trtid year;
        Model var = location | trtid | year/ dfm=satterth;
        Random block(location);
```

```
  Lsmean location trtid location*trtid;
Run;
```

Statistical Design And SAS Program For Nonparametric Data

Freidman's 2-Way ANOVA by Ranks

Ranks using the test stastistic:

$$[(12/Nk(k+1)) \sum^{k}_{j=1} R^{2}_{j}] -3N(k+1)$$

Where:

N = number of rows

K = number of columns (variables)

R_j = sum of ranks in the jth column

$\sum^{k}_{j=1}$ directs one to sum the squares of sums of ranks over all conditions

SAS Program

```
Proc rank data = input;
        By block;
        Var variable name;
        Ranks Rvariable name;
Run;
Proc ANOVA;
        Class block trtid;
        Model Rvariable name = block trtid;
Run;
```

APPENDIX C

Additional Data Tables For Chapter II

Table C.1. Soil pH means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	7.46	0.40	7.54	0.11	7.42	0.19	7.47	0.26
	Fertilizer	7.57	0.12	7.33	0.37	7.42	0.20	7.44	0.26
	Biosolids 50	7.59	0.19	7.42	0.27	7.28	0.20	7.43	0.25
	Biosolids 100	7.53	0.30	7.30	0.34	7.23	0.24	7.35	0.31
	Biosolids 150	7.56	0.22	7.42	0.31	7.10	0.28	7.36	0.33
	Biosolids 200	7.48	0.22	7.36	0.28	7.04	0.24	7.29	0.30
	Biosolids 250	7.41	0.29	7.39	0.28	7.04	0.19	7.28	0.30
Treatment p value		0.4842		0.7550		0.0001		0.0198	
Sand	Control	7.35	0.15	7.38	0.30	7.15	0.14	7.29	0.23
	Fertilizer	7.34	0.17	7.27	0.33	7.15	0.17	7.25	0.24
	Biosolids 50	7.22	0.09	7.45	0.28	6.85	0.16	7.17	0.31
	Biosolids 100	7.33	0.07	7.55	0.08	6.74	0.13	7.21	0.36
	Biosolids 150	7.32	0.07	7.28	0.45	6.50	0.12	7.03	0.47
	Biosolids 200	7.26	0.13	7.36	0.37	6.47	0.13	7.03	0.47
	Biosolids 250	7.23	0.16	7.39	0.26	6.49	0.16	7.04	0.44
Treatment p value		0.0741		0.6144		0.0001		0.0002	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.2. Soil pH means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	7.47	0.26	7.47	0.11	7.55	0.12	7.50	0.17
	Fertilizer	7.54	0.12	7.52	0.15	7.56	0.06	7.54	0.11
	Biosolids 50	7.62	0.13	7.49	0.08	7.54	0.11	7.55	0.12
	Biosolids 100	7.59	0.20	7.54	0.18	7.54	0.12	7.56	0.16
	Biosolids 150	7.63	0.13	7.44	0.15	7.52	0.11	7.53	0.15
	Biosolids 200	7.65	0.20	7.53	0.13	7.57	0.12	7.58	0.16
	Biosolids 250	7.61	0.20	7.54	0.16	7.52	0.09	7.56	0.15
Treatment p value		0.0875		0.7115		0.8583		0.4563	
Sand	Control	7.36	0.20	7.45	0.30	7.40	0.09	7.40	0.21
	Fertilizer	7.37	0.12	7.54	0.14	7.41	0.05	7.44	0.13
	Biosolids 50	7.34	0.15	7.20	0.35	7.41	0.12	7.32	0.24
	Biosolids 100	7.41	0.13	7.39	0.34	7.33	0.15	7.38	0.22
	Biosolids 150	7.46	0.06	7.33	0.41	7.34	0.09	7.38	0.24
	Biosolids 200	7.38	0.23	7.35	0.38	7.30	0.15	7.35	0.26
	Biosolids 250	7.40	0.10	7.41	0.31	7.33	0.16	7.38	0.21
Treatment p value		0.3969		0.5702		0.1503		0.5863	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.3. Soil pH means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	7.45	0.24	7.53	0.15	7.61	0.05	7.53	0.17
	Fertilizer	7.52	0.16	7.60	0.12	7.59	0.08	7.57	0.12
	Biosolids 50	7.59	0.13	7.51	0.23	7.61	0.06	7.57	0.16
	Biosolids 100	7.58	0.16	7.55	0.15	7.60	0.09	7.58	0.13
	Biosolids 150	7.61	0.13	7.62	0.15	7.57	0.08	7.60	0.12
	Biosolids 200	7.54	0.13	7.58	0.15	7.59	0.09	7.57	0.12
	Biosolids 250	7.54	0.12	7.49	0.21	7.60	0.10	7.54	0.15
Treatment p value		0.0690		0.7122		0.7195		0.6861	
Sand	Control	7.37	0.18	7.59	0.13	7.47	0.07	7.48	0.16
	Fertilizer	7.42	0.05	7.57	0.13	7.45	0.03	7.48	0.10
	Biosolids 50	7.34	0.12	7.60	0.09	7.47	0.06	7.47	0.14
	Biosolids 100	7.39	0.11	7.39	0.32	7.44	0.11	7.41	0.17
	Biosolids 150	7.46	0.08	7.54	0.20	7.45	0.04	7.48	0.13
	Biosolids 200	7.34	0.21	7.52	0.16	7.44	0.05	7.43	0.17
	Biosolids 250	7.41	0.18	7.46	0.17	7.44	0.05	7.44	0.14
Treatment p value		0.2989		0.2326		0.0273		0.2325	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.4. Soil electrical conductivity (dS m^{-1}) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.58	0.13	0.70	0.14	0.75	0.23	0.67	0.18
	Fertilizer	0.52	0.15	0.61	0.23	0.74	0.34	0.62	0.26
	Biosolids 50	0.52	0.13	0.66	0.20	0.71	0.24	0.63	0.20
	Biosolids 100	0.55	0.12	0.79	0.23	0.79	0.26	0.71	0.23
	Biosolids 150	0.57	0.15	0.84	0.20	0.95	0.28	0.79	0.26
	Biosolids 200	0.62	0.20	0.87	0.13	0.84	0.22	0.78	0.21
	Biosolids 250	0.69	0.14	0.99	0.17	0.93	0.20	0.87	0.21
Treatment p value		0.0069		0.0001		0.1796		0.0001	
Sand	Control	0.06	0.11	0.05	0.01	0.05	0.01	0.05	0.01
	Fertilizer	0.06	0.01	0.06	0.01	0.05	0.01	0.05	0.01
	Biosolids 50	0.11	0.02	0.10	0.03	0.06	0.01	0.09	0.03
	Biosolids 100	0.14	0.03	0.15	0.06	0.08	0.04	0.12	0.05
	Biosolids 150	0.16	0.03	0.16	0.04	0.10	0.07	0.14	0.06
	Biosolids 200	0.21	0.05	0.25	0.08	0.12	0.08	0.19	0.09
	Biosolids 250	0.24	0.05	0.34	0.09	0.14	0.08	0.24	0.11
Treatment p value		0.0001		0.0001		0.0003		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.5. Soil electrical conductivity (dS m^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.46	0.13	0.57	0.13	0.60	0.25	0.55	0.18
	Fertilizer	0.49	0.16	0.63	0.25	0.58	0.21	0.57	0.21
	Biosolids 50	0.46	0.12	0.58	0.17	0.55	0.15	0.53	0.15
	Biosolids 100	0.53	0.06	0.67	0.17	0.56	0.08	0.59	0.12
	Biosolids 150	0.49	0.09	0.70	0.25	0.63	0.24	0.61	0.22
	Biosolids 200	0.44	0.17	0.69	0.24	0.59	0.24	0.58	0.23
	Biosolids 250	0.57	0.09	0.81	0.30	0.73	0.17	0.70	0.22
Treatment p value		0.2272		0.0476		0.3900		0.0465	
Sand	Control	0.06	0.01	0.06	0.00	0.06	0.01	0.06	0.01
	Fertilizer	0.06	0.01	0.06	0.01	0.05	0.01	0.06	0.01
	Biosolids 50	0.06	0.01	0.11	0.03	0.07	0.01	0.08	0.03
	Biosolids 100	0.06	0.01	0.17	0.06	0.08	0.04	0.10	0.06
	Biosolids 150	0.07	0.01	0.19	0.06	0.09	0.04	0.11	0.07
	Biosolids 200	0.08	0.01	0.28	0.08	0.11	0.05	0.16	0.10
	Biosolids 250	0.08	0.01	0.29	0.12	0.13	0.06	0.16	0.12
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.6. Soil total carbon (%) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.55	0.07	0.53	0.08	0.60	0.08	0.56	0.08
	Fertilizer	0.56	0.11	0.50	0.05	0.58	0.07	0.55	0.08
	Biosolids 50	0.59	0.08	0.52	0.05	0.64	0.08	0.58	0.09
	Biosolids 100	0.57	0.09	0.54	0.06	0.64	0.09	0.58	0.09
	Biosolids 150	0.56	0.10	0.53	0.10	0.89	0.70	0.66	0.43
	Biosolids 200	0.56	0.09	0.52	0.06	0.62	0.11	0.56	0.10
	Biosolids 250	0.60	0.09	0.54	0.07	0.66	0.16	0.60	0.12
Treatment p value		0.4320		0.6733		0.3082		0.3018	
Sand	Control	0.29	0.01	0.30	0.03	0.27	0.04	0.29	0.03
	Fertilizer	0.29	0.02	0.31	0.04	0.26	0.04	0.29	0.04
	Biosolids 50	0.31	0.02	0.31	0.03	0.29	0.05	0.30	0.04
	Biosolids 100	0.31	0.04	0.32	0.04	0.35	0.15	0.33	0.09
	Biosolids 150	0.33	0.02	0.32	0.04	0.36	0.19	0.33	0.11
	Biosolids 200	0.32	0.07	0.38	0.18	0.29	0.06	0.33	0.12
	Biosolids 250	0.34	0.04	0.41	0.19	0.30	0.05	0.35	0.12
Treatment p value		0.0728		0.2473		0.2443		0.1032	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.7. Soil total carbon (%) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.50	0.07	0.97	1.33	0.57	0.07	0.68	0.77
	Fertilizer	0.50	0.06	0.87	0.56	0.54	0.09	0.64	0.36
	Biosolids 50	0.50	0.08	1.87	1.86	0.61	0.13	0.99	1.21
	Biosolids 100	0.54	0.05	0.64	0.13	0.58	0.07	0.59	0.10
	Biosolids 150	0.53	0.06	1.84	1.75	0.59	0.08	0.99	1.15
	Biosolids 200	0.49	0.09	0.79	0.56	0.55	0.07	0.61	0.34
	Biosolids 250	0.56	0.07	1.82	1.51	0.64	0.11	1.01	1.02
Treatment p value		0.0462		0.0194		0.2851		0.0599	
Sand	Control	0.28	0.02	0.33	0.02	0.29	0.06	0.30	0.04
	Fertilizer	0.79	1.44	0.32	0.02	0.28	0.05	0.47	0.83
	Biosolids 50	0.28	0.02	0.33	0.04	0.28	0.05	0.30	0.04
	Biosolids 100	0.29	0.01	0.32	0.02	0.30	0.05	0.30	0.03
	Biosolids 150	0.29	0.03	0.33	0.02	0.29	0.04	0.30	0.04
	Biosolids 200	0.29	0.02	0.38	0.14	0.28	0.05	0.31	0.10
	Biosolids 250	0.30	0.02	0.38	0.15	0.30	0.07	0.33	0.10
Treatment p value		0.4519		0.5063		0.5877		0.5174	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.8. Soil total cation exchange capacity (cmol (+) kg^{-1}) means at a depth of 15 to 30 cm fo 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	3.25	3.33	1.88	0.35	3.25	1.49	2.79	2.13
	Fertilizer	2.00	0.93	2.13	1.46	3.38	2.77	2.50	1.91
	Biosolids 50	1.88	0.83	2.13	0.64	3.75	1.49	2.58	1.32
	Biosolids 100	1.63	0.92	3.13	1.55	6.63	5.71	3.79	3.93
	Biosolids 150	3.25	4.03	4.00	3.12	4.63	2.20	3.96	3.11
	Biosolids 200	1.63	0.74	2.25	0.71	3.63	1.69	2.50	1.38
	Biosolids 250	1.63	0.74	2.13	0.83	3.88	1.89	2.54	1.56
Treatment p value		0.2840		0.0232		0.1293		0.0331	
Sand	Control	0.13	0.35	1.00	0.00	0.75	0.46	0.63	0.49
	Fertilizer	0.63	0.52	0.88	0.35	0.88	0.35	0.79	0.41
	Biosolids 50	0.50	0.53	0.88	0.35	1.00	0.53	0.79	0.51
	Biosolids 100	0.63	0.74	1.00	0.00	0.75	0.46	0.79	0.51
	Biosolids 150	1.13	1.89	1.13	0.35	0.63	0.52	0.96	1.12
	Biosolids 200	0.88	0.99	0.75	0.46	2.50	3.51	1.38	2.18
	Biosolids 250	0.50	0.53	1.25	1.16	0.38	0.52	0.71	0.86
Treatment p value		0.4934		0.5655		0.0791		0.2093	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.9. Soil total cation exchange capacity (cmol (+) kg^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	1.63	0.74	1.38	0.52	2.50	0.76	1.83	0.82
	Fertilizer	1.25	0.46	1.75	0.89	1.75	0.46	1.58	0.65
	Biosolids 50	1.63	0.52	1.75	0.89	3.00	1.07	2.13	1.03
	Biosolids 100	1.75	0.71	2.38	0.52	3.00	2.45	2.38	1.53
	Biosolids 150	1.75	0.71	3.00	1.31	2.38	0.74	2.38	1.06
	Biosolids 200	1.38	0.52	2.00	1.07	1.75	0.71	1.71	0.81
	Biosolids 250	1.75	0.46	2.63	1.30	2.50	0.76	2.29	0.95
Treatment p value		0.2136		0.0140		0.1291		0.0053	
Sand	Control	0.50	0.76	0.63	0.52	1.13	0.35	0.75	0.61
	Fertilizer	0.13	0.35	0.75	0.46	1.00	0.00	0.63	0.49
	Biosolids 50	0.13	0.35	0.75	0.46	0.88	0.35	0.58	0.50
	Biosolids 100	0.38	0.52	0.50	0.53	0.75	0.71	0.54	0.59
	Biosolids 150	0.00	0.00	0.25	0.46	0.75	0.71	0.33	0.56
	Biosolids 200	0.25	0.46	0.75	0.71	0.88	0.35	0.63	0.58
	Biosolids 250	1.50	3.12	0.75	0.71	0.50	0.76	0.92	1.86
Treatment p value		0.2348		0.4526		0.3479		0.4081	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.10. Soil exchangable calcium (cmol (+) kg^{-1}) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	19.70	2.29	17.64	2.98	15.25	1.38	17.53	2.88
	Fertilizer	19.69	2.82	19.00	1.77	15.13	1.34	17.94	2.85
	Biosolids 50	20.21	4.79	18.99	1.12	14.87	1.76	18.02	3.71
	Biosolids 100	27.82	4.65	32.34	8.35	25.96	3.32	28.70	6.22
	Biosolids 150	28.57	5.12	30.14	6.98	24.33	3.05	27.68	5.65
	Biosolids 200	28.95	3.70	30.20	6.60	22.94	4.03	27.36	5.73
	Biosolids 250	30.51	3.43	31.70	5.61	23.25	2.99	28.49	5.52
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	6.82	0.93	6.76	0.84	5.52	0.88	6.37	1.04
	Fertilizer	6.74	0.69	6.51	0.96	5.61	1.14	6.29	1.03
	Biosolids 50	6.55	0.76	6.00	0.89	5.01	0.82	5.85	1.02
	Biosolids 100	9.42	0.77	7.25	0.91	6.16	1.10	7.61	1.65
	Biosolids 150	12.30	3.05	7.79	1.09	6.61	0.60	8.90	3.10
	Biosolids 200	11.19	0.98	7.84	1.41	6.79	1.08	8.60	2.22
	Biosolids 250	12.52	1.59	9.03	1.49	7.26	0.70	9.60	2.56
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.11. Soil exchangable calcium (cmol (+) kg^{-1}) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	19.78	3.05	22.27	3.79	16.22	1.16	19.42	3.75
	Fertilizer	20.17	2.28	21.61	2.62	15.62	2.08	19.13	3.43
	Biosolids 50	22.57	6.97	21.51	2.43	15.50	1.54	19.86	5.24
	Biosolids 100	31.92	10.03	37.86	9.18	28.42	7.58	32.73	9.47
	Biosolids 150	32.47	11.47	35.73	9.27	29.48	6.80	32.56	9.33
	Biosolids 200	33.53	11.06	34.28	8.30	27.81	4.95	31.87	8.62
	Biosolids 250	33.24	11.17	35.93	8.21	29.72	7.15	32.96	8.99
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	6.81	0.82	7.12	0.72	6.56	0.51	6.83	0.71
	Fertilizer	6.93	0.59	7.39	0.85	8.04	2.46	7.45	1.54
	Biosolids 50	6.90	1.00	7.44	0.99	7.57	2.52	7.30	1.62
	Biosolids 100	9.59	1.08	9.14	1.24	7.50	1.85	8.74	1.64
	Biosolids 150	9.78	1.33	8.51	1.21	8.05	0.97	8.78	1.35
	Biosolids 200	8.99	1.08	8.58	1.04	7.85	1.43	8.47	1.24
	Biosolids 250	9.64	1.13	8.72	1.16	7.47	2.20	8.61	1.76
Treatment p value		0.0001		0.0001		0.7203		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.12. Soil exchangable calcium (cmol (+) kg^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	19.91	2.59	22.17	3.67	15.87	2.03	19.32	3.80
	Fertilizer	19.12	1.97	20.99	3.65	14.85	1.28	18.32	3.55
	Biosolids 50	20.50	1.55	22.39	4.68	15.36	1.65	19.42	4.18
	Biosolids 100	31.75	4.61	37.63	6.38	28.61	4.27	32.66	6.24
	Biosolids 150	30.44	4.99	38.47	11.43	26.25	4.97	31.72	9.05
	Biosolids 200	27.92	6.20	33.68	9.09	24.62	6.42	28.74	8.01
	Biosolids 250	32.27	6.43	35.80	8.38	28.58	4.75	32.21	7.06
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	6.82	0.81	8.28	0.65	7.37	1.11	7.49	1.04
	Fertilizer	6.78	1.10	8.25	0.87	6.50	0.98	7.18	1.23
	Biosolids 50	6.84	0.85	8.13	0.96	7.54	2.24	7.50	1.52
	Biosolids 100	9.60	1.60	10.35	1.49	8.96	1.33	9.64	1.53
	Biosolids 150	9.05	0.94	10.52	0.95	8.65	0.72	9.41	1.17
	Biosolids 200	9.46	1.18	9.96	1.43	8.78	1.26	9.40	1.33
	Biosolids 250	9.54	1.35	9.97	0.77	7.92	2.25	9.15	1.76
Treatment p value		0.0001		0.0001		0.0076		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.13. Soil exchangable potassium (cmol (+) kg^{-1}) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.68	0.11	0.63	0.19	0.70	0.18	0.67	0.16
	Fertilizer	0.68	0.17	0.64	0.26	0.77	0.34	0.70	0.26
	Biosolids 50	0.82	0.31	0.58	0.24	0.61	0.25	0.67	0.28
	Biosolids 100	0.89	0.21	0.62	0.29	0.84	0.31	0.78	0.29
	Biosolids 150	1.01	0.16	0.53	0.27	1.07	0.29	0.87	0.34
	Biosolids 200	1.04	0.21	0.53	0.23	0.99	0.36	0.85	0.35
	Biosolids 250	1.19	0.23	0.61	0.17	1.05	0.45	0.95	0.39
Treatment p value		0.0001		0.4755		0.0001		0.0001	
Sand	Control	0.28	0.56	0.19	0.32	0.04	0.01	0.17	0.37
	Fertilizer	0.18	0.30	0.05	0.02	0.05	0.03	0.10	0.18
	Biosolids 50	0.65	1.13	0.05	0.01	0.06	0.03	0.25	0.69
	Biosolids 100	0.17	0.04	0.08	0.05	0.09	0.05	0.11	0.06
	Biosolids 150	0.31	0.15	0.10	0.02	0.12	0.04	0.17	0.13
	Biosolids 200	0.67	0.49	0.13	0.04	0.16	0.08	0.32	0.37
	Biosolids 250	1.12	1.05	0.18	0.04	0.16	0.06	0.49	0.77
Treatment p value		0.0105		0.1312		0.0001		0.0046	

N = 8 for each year and 24 for mean
SD = standard deviation

Table C.14. Soil exchangable potassium (cmol (+) kg^{-1}) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.36	0.12	0.33	0.06	0.43	0.12	0.37	0.11
	Fertilizer	0.32	0.09	0.33	0.12	0.44	0.14	0.37	0.13
	Biosolids 50	0.36	0.12	0.32	0.09	0.46	0.12	0.38	0.12
	Biosolids 100	0.36	0.09	0.34	0.06	0.56	0.32	0.42	0.21
	Biosolids 150	0.36	0.13	0.34	0.10	0.52	0.26	0.41	0.19
	Biosolids 200	0.37	0.13	0.31	0.10	0.53	0.16	0.40	0.16
	Biosolids 250	0.39	0.12	0.35	0.10	0.58	0.25	0.44	0.19
Treatment p value		0.4106		0.7140		0.2281		0.1278	
Sand	Control	0.53	1.01	0.04	0.01	0.05	0.02	0.20	0.61
	Fertilizer	0.21	0.29	0.04	0.01	0.06	0.03	0.10	0.18
	Biosolids 50	0.11	0.10	0.04	0.02	0.05	0.02	0.07	0.07
	Biosolids 100	1.17	1.71	0.05	0.01	0.06	0.02	0.43	1.09
	Biosolids 150	0.35	0.64	0.07	0.04	0.07	0.03	0.16	0.38
	Biosolids 200	0.55	1.12	0.05	0.01	0.07	0.05	0.22	0.66
	Biosolids 250	0.37	0.46	0.09	0.11	0.07	0.06	0.18	0.30
Treatment p value		0.2230		0.0843		0.5521		0.2980	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.15. Soil exchangable potassium (cmol (+) kg^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.30	0.10	0.30	0.08	0.37	0.08	0.33	0.09
	Fertilizer	0.31	0.10	0.35	0.13	0.38	0.14	0.35	0.12
	Biosolids 50	0.32	0.08	0.33	0.14	0.42	0.12	0.36	0.12
	Biosolids 100	0.36	0.05	0.35	0.06	0.44	0.08	0.38	0.07
	Biosolids 150	0.32	0.08	0.34	0.10	0.44	0.13	0.36	0.11
	Biosolids 200	0.29	0.14	0.31	0.12	0.39	0.14	0.33	0.13
	Biosolids 250	0.38	0.10	0.38	0.13	0.49	0.12	0.42	0.12
Treatment p value		0.2282		0.3939		0.0676		0.0704	
Sand	Control	0.22	0.36	0.03	0.01	0.06	0.02	0.10	0.22
	Fertilizer	0.19	0.41	0.04	0.02	0.06	0.02	0.10	0.24
	Biosolids 50	0.13	0.27	0.04	0.02	0.06	0.02	0.07	0.15
	Biosolids 100	0.05	0.01	0.04	0.01	0.06	0.02	0.05	0.02
	Biosolids 150	0.40	0.97	0.04	0.00	0.06	0.02	0.16	0.56
	Biosolids 200	0.59	1.12	0.06	0.05	0.07	0.06	0.24	0.67
	Biosolids 250	0.11	0.16	0.06	0.04	0.07	0.04	0.08	0.09
Treatment p value		0.2873		0.2281		0.8671		0.4551	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.16. Soil exchangable magnesium (cmol (+) kg^{-1}) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	2.04	0.73	1.34	0.61	1.72	0.90	1.70	0.78
	Fertilizer	2.09	0.81	1.58	0.78	1.67	0.85	1.78	0.81
	Biosolids 50	2.36	0.80	1.92	0.70	1.89	0.93	2.06	0.81
	Biosolids 100	2.91	0.79	2.21	0.88	1.88	1.81	2.33	0.99
	Biosolids 150	3.27	1.16	2.11	0.74	2.62	1.26	2.67	1.14
	Biosolids 200	4.16	0.85	2.11	0.38	1.84	0.92	2.70	1.28
	Biosolids 250	4.35	1.39	2.37	0.45	2.18	1.07	2.97	1.41
Treatment p value		0.0001		0.0021		0.0047		0.0001	
Sand	Control	0.11	0.04	0.11	0.03	0.08	0.02	0.10	0.03
	Fertilizer	0.11	0.04	0.10	0.03	0.06	0.02	0.09	0.03
	Biosolids 50	0.39	0.11	0.23	0.07	0.17	0.06	0.26	0.12
	Biosolids 100	0.65	0.19	0.40	0.17	0.21	0.08	0.42	0.24
	Biosolids 150	1.20	0.13	0.49	0.10	0.31	0.07	0.67	0.41
	Biosolids 200	1.51	0.33	0.62	0.20	0.38	0.05	0.83	0.54
	Biosolids 250	1.87	0.35	1.11	0.41	0.46	0.09	1.15	0.66
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.17. Soil exchangable magnesium (cmol (+) kg^{-1}) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	1.13	0.17	1.67	0.10	1.20	0.37	1.34	0.23
	Fertilizer	1.07	0.18	1.12	0.24	1.25	0.53	1.15	0.35
	Biosolids 50	1.14	0.23	1.08	0.24	1.34	0.46	1.19	0.33
	Biosolids 100	1.26	0.36	1.16	0.28	1.10	0.40	1.17	0.34
	Biosolids 150	1.29	0.38	1.17	0.37	1.31	0.79	1.25	0.53
	Biosolids 200	1.34	0.32	1.14	0.36	1.08	0.46	1.18	0.38
	Biosolids 250	1.43	0.44	1.36	0.30	1.22	0.60	1.33	0.45
Treatment p value		0.0064		0.0795		0.6374		0.3836	
Sand	Control	0.15	0.04	0.13	0.03	0.09	0.02	0.13	0.04
	Fertilizer	0.13	0.04	0.12	0.03	0.11	0.03	0.12	0.03
	Biosolids 50	0.16	0.04	0.12	0.03	0.11	0.03	0.13	0.04
	Biosolids 100	0.17	0.04	0.16	0.03	0.12	0.03	0.15	0.04
	Biosolids 150	0.19	0.05	0.16	0.01	0.13	0.03	0.16	0.04
	Biosolids 200	0.18	0.03	0.18	0.02	0.14	0.02	0.17	0.03
	Biosolids 250	0.20	0.04	0.28	0.18	0.13	0.06	0.21	0.13
Treatment p value		0.0001		0.0006		0.0490		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.18. Soil exchangable magnesium (cmol (+) kg^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.90	0.17	0.84	0.20	1.07	0.37	0.93	0.27
	Fertilizer	0.89	0.16	0.97	0.24	1.00	0.37	0.96	0.26
	Biosolids 50	0.90	0.09	0.97	0.21	1.09	0.44	0.99	0.29
	Biosolids 100	1.17	0.25	1.07	0.17	0.93	0.22	1.06	0.23
	Biosolids 150	1.11	0.23	1.08	0.25	0.90	0.28	1.03	0.26
	Biosolids 200	0.94	0.27	0.93	0.31	0.80	0.25	0.89	0.27
	Biosolids 250	1.29	0.22	1.15	0.31	1.05	0.30	1.16	0.29
Treatment p value		0.0001		0.0935		0.1954		0.0177	
Sand	Control	0.16	0.04	0.15	0.02	0.10	0.03	0.14	0.04
	Fertilizer	0.16	0.04	0.15	0.04	0.10	0.04	0.14	0.05
	Biosolids 50	0.16	0.04	0.14	0.04	0.09	0.05	0.13	0.05
	Biosolids 100	0.19	0.05	0.16	0.04	0.10	0.05	0.15	0.06
	Biosolids 150	0.17	0.04	0.17	0.03	0.11	0.05	0.15	0.05
	Biosolids 200	0.19	0.03	0.19	0.02	0.11	0.05	0.16	0.05
	Biosolids 250	0.19	0.19	0.20	0.05	0.11	0.06	0.17	0.04
Treatment p value		0.0919		0.0007		0.4794		0.0052	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.19. Soil exchangable sodium (cmol (+) kg^{-1}) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	1.53	0.34	1.04	0.46	1.03	0.39	1.20	0.45
	Fertilizer	2.30	2.59	1.00	0.75	1.17	0.52	1.49	1.62
	Biosolids 50	2.63	3.20	1.15	0.73	1.05	0.52	1.61	1.98
	Biosolids 100	1.56	0.60	0.98	0.47	1.00	0.72	1.18	0.64
	Biosolids 150	1.75	0.50	0.95	0.60	1.04	0.86	1.25	0.74
	Biosolids 200	1.63	0.62	0.80	0.78	0.48	0.30	0.97	0.76
	Biosolids 250	2.28	1.10	0.86	0.41	0.57	0.29	1.23	1.01
Treatment p value		0.7569		0.8503		0.0384		0.6603	
Sand	Control	0.06	0.06	0.04	0.02	0.01	0.01	0.04	0.04
	Fertilizer	0.09	0.07	0.04	0.01	0.02	0.02	0.05	0.05
	Biosolids 50	0.19	0.17	0.14	0.29	0.01	0.01	0.11	0.20
	Biosolids 100	0.31	0.22	0.09	0.03	0.03	0.01	0.14	0.17
	Biosolids 150	0.51	0.46	0.08	0.03	0.02	0.01	0.20	0.34
	Biosolids 200	0.46	0.35	0.17	0.19	0.03	0.01	0.22	0.29
	Biosolids 250	0.67	0.32	0.16	0.03	0.03	0.01	0.29	0.33
Treatment p value		0.0001		0.2101		0.0110		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.20. Soil exchangable sodium (cmol (+) kg^{-1}) means at a depth of 15 to 30 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.47	0.09	0.54	0.23	0.48	0.38	0.50	0.25
	Fertilizer	0.41	0.14	0.51	0.27	0.36	0.26	0.43	0.23
	Biosolids 50	0.42	0.16	0.43	0.14	0.35	0.18	0.40	0.46
	Biosolids 100	0.57	0.57	0.32	0.15	0.41	0.42	0.43	0.41
	Biosolids 150	0.50	0.26	0.32	0.18	0.26	0.19	0.36	0.23
	Biosolids 200	0.67	0.49	0.44	0.35	0.27	0.21	0.46	0.39
	Biosolids 250	0.70	0.34	0.39	0.18	0.26	0.16	0.45	0.29
Treatment p value		0.4528		0.2428		0.5782		0.8386	
Sand	Control	0.18	0.25	0.23	0.40	0.01	0.01	0.14	0.28
	Fertilizer	0.28	0.29	0.06	0.11	0.44	1.19	0.26	0.70
	Biosolids 50	0.28	0.24	0.02	0.01	0.01	0.01	0.11	0.19
	Biosolids 100	0.58	0.58	0.04	0.02	0.02	0.01	0.21	0.42
	Biosolids 150	0.42	0.50	0.13	0.17	0.03	0.03	0.20	0.34
	Biosolids 200	0.31	0.23	0.05	0.02	0.02	0.01	0.12	0.18
	Biosolids 250	0.31	0.35	0.12	0.19	0.02	0.01	0.15	0.25
Treatment p value		0.0491		0.3086		0.4344		0.6847	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.21. Soil exchangable sodium (cmol (+) kg^{-1}) means at a depth of 30 to 45 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.32	0.09	0.42	0.21	0.30	0.22	0.35	0.18
	Fertilizer	0.39	0.21	0.46	0.26	0.30	0.24	0.39	0.24
	Biosolids 50	0.37	0.14	0.47	0.22	0.25	0.10	0.36	0.18
	Biosolids 100	0.34	0.12	0.31	0.23	0.18	0.07	0.28	0.16
	Biosolids 150	0.45	0.33	0.35	0.26	0.19	0.10	0.33	0.26
	Biosolids 200	0.33	0.16	0.26	0.17	0.25	0.29	0.28	0.21
	Biosolids 250	0.65	0.60	0.36	0.22	0.27	0.21	0.43	0.41
Treatment p value		0.2224		0.1112		0.8217		0.2787	
Sand	Control	0.18	0.26	0.02	0.02	0.01	0.01	0.07	0.16
	Fertilizer	0.13	0.19	0.02	0.01	0.01	0.03	0.05	0.12
	Biosolids 50	0.10	0.12	0.13	0.32	0.01	0.01	0.08	0.20
	Biosolids 100	0.31	0.38	0.04	0.02	0.05	0.09	0.13	0.25
	Biosolids 150	0.15	0.20	0.03	0.03	0.01	0.01	0.07	0.13
	Biosolids 200	0.36	0.51	0.21	0.51	0.02	0.01	0.20	0.42
	Biosolids 250	0.26	0.35	0.04	0.03	0.03	0.07	0.11	0.22
Treatment p value		0.2218		0.5610		0.5514		0.2527	

N = 8 for each year and 24 for mean

SD = standard deviation

Table C.22. Penetration resistance (MPa) at 6 cm depth increments.

		Depth									
Site	Treatment	0-6 cm	6-12 cm	12-18 cm	18-24 cm	24-30 cm	30-36 cm	36-42 cm	42-48 cm	48-54 cm	54-60 cm
Silt Loam	Control	0.38	0.47	0.60	0.97	1.08	1.10	1.15	1.38	1.33	1.05
	Fertilizer	0.38	0.49	0.61	1.02	1.20	1.34	1.44	1.29	1.10	1.11
	Biosolids 50	0.36	0.49	0.59	0.89	1.05	1.15	1.21	1.12	1.21	1.16
	Biosolids 100	0.31	0.46	0.51	1.00	1.12	1.17	1.31	1.15	1.22	1.24
	Biosolids 150	0.31	0.49	0.61	0.96	1.13	1.17	1.24	1.28	1.30	1.26
	Biosolids 200	0.30	0.47	0.56	0.96	1.20	1.15	1.20	1.44	1.61	1.32
	Biosolids 250	0.29	0.46	0.56	0.89	1.12	1.14	1.10	1.15	1.29	1.28
Treatment p value		0.0001	0.8696	0.4286	0.4825	0.5723	0.4739	0.3323	0.267	0.1528	0.5477
Sand	Control	0.30	0.49	0.71	1.66	2.35	2.47	2.56	2.48	2.48	2.42
	Fertilizer	0.29	0.44	0.65	1.56	2.32	2.51	2.50	2.54	2.56	2.57
	Biosolids 50	0.30	0.50	0.75	1.54	2.18	2.33	2.45	2.56	2.50	2.55
	Biosolids 100	0.25	0.45	0.70	1.55	2.15	2.40	2.43	2.41	2.50	2.53
	Biosolids 150	0.23	0.47	0.68	1.48	2.21	2.42	2.45	2.47	2.48	2.58
	Biosolids 200	0.24	0.42	0.68	1.60	2.34	2.55	2.67	2.68	2.63	2.65
	Biosolids 250	0.21	0.39	0.60	1.28	2.09	2.41	2.60	2.63	2.61	2.65
Treatment p value		0.0016	0.0084	0.3752	0.1235	0.1825	0.5602	0.3704	0.3651	0.8392	0.696

APPENDIX D

Additional Data Tables For Chapter III

Table D.1. Soil total potassium (%) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.18	0.05	0.13	0.02	0.17	0.02	0.16	0.04
	Fertilizer	0.18	0.05	0.14	0.03	0.17	0.03	0.16	0.04
	Biosolids 50	0.15	0.05	0.14	0.03	0.16	0.04	0.15	0.04
	Biosolids 100	0.16	0.05	0.13	0.02	0.16	0.03	0.15	0.04
	Biosolids 150	0.18	0.07	0.12	0.01	0.16	0.03	0.15	0.05
	Biosolids 200	0.18	0.05	0.12	0.01	0.15	0.03	0.15	0.04
	Biosolids 250	0.16	0.05	0.12	0.02	0.16	0.03	0.15	0.04
Treatment p value		0.8984		0.0491		0.1852		0.7429	
Sand	Control	0.10	0.00	0.06	0.01	0.07	0.01	0.08	0.02
	Fertilizer	0.10	0.00	0.06	0.01	0.06	0.01	0.08	0.02
	Biosolids 50	0.10	0.00	0.05	0.01	0.06	0.01	0.07	0.02
	Biosolids 100	0.10	0.00	0.05	0.01	0.06	0.01	0.07	0.02
	Biosolids 150	0.10	0.00	0.06	0.00	0.06	0.01	0.07	0.02
	Biosolids 200	0.10	0.00	0.05	0.00	0.06	0.01	0.07	0.02
	Biosolids 250	0.10	0.00	0.06	0.01	0.06	0.01	0.07	0.02
Treatment p value				0.1479		0.4764		0.3517	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.2. Soil total magnesium (%) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.13	0.02	0.11	0.02	0.13	0.03	0.13	0.02
	Fertilizer	0.13	0.02	0.12	0.03	0.13	0.03	0.13	0.03
	Biosolids 50	0.15	0.03	0.13	0.03	0.13	0.03	0.14	0.03
	Biosolids 100	0.16	0.03	0.13	0.03	0.14	0.03	0.14	0.03
	Biosolids 150	0.18	0.01	0.14	0.03	0.15	0.02	0.16	0.03
	Biosolids 200	0.18	0.03	0.14	0.02	0.16	0.02	0.16	0.03
	Biosolids 250	0.21	0.03	0.17	0.02	0.16	0.03	0.18	0.03
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	0.06	0.01	0.05	0.00	0.05	0.01	0.05	0.01
	Fertilizer	0.06	0.01	0.05	0.01	0.05	0.01	0.05	0.01
	Biosolids 50	0.07	0.01	0.06	0.01	0.06	0.01	0.06	0.01
	Biosolids 100	0.07	0.01	0.06	0.01	0.06	0.01	0.06	0.01
	Biosolids 150	0.08	0.01	0.07	0.00	0.07	0.00	0.07	0.01
	Biosolids 200	0.10	0.01	0.07	0.01	0.07	0.01	0.08	0.02
	Biosolids 250	0.12	0.02	0.09	0.01	0.08	0.01	0.09	0.02
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.3. Soil total boron (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	26.4	2.7	13.3	1.1	13.2	9.6	17.6	8.4
	Fertilizer	25.5	2.4	16.0	1.5	17.2	9.0	19.4	6.8
	Biosolids 50	25.1	2.1	14.9	3.0	10.2	5.3	16.7	7.3
	Biosolids 100	24.9	1.9	16.1	1.6	13.8	7.8	18.2	6.7
	Biosolids 150	25.3	2.3	16.9	2.8	11.7	7.9	18.0	7.5
	Biosolids 200	24.9	3.0	15.5	1.2	13.0	7.2	17.8	6.8
	Biosolids 250	24.5	2.8	16.5	2.3	12.9	7.3	18.0	6.7
Treatment p value		0.7738		0.0137		0.1841		0.5686	
Sand	Control	30.3	2.9	19.6	4.6	12.1	5.3	20.6	8.7
	Fertilizer	28.9	2.0	18.8	2.3	14.1	6.8	20.6	7.5
	Biosolids 50	30.3	2.0	19.5	4.2	14.7	7.0	21.5	8.1
	Biosolids 100	29.1	2.0	20.0	4.2	13.7	5.9	21.0	7.7
	Biosolids 150	30.9	1.9	17.9	1.1	17.2	5.5	22.0	7.2
	Biosolids 200	64.8	95.5	19.2	1.4	12.7	5.3	32.2	57.8
	Biosolids 250	30.9	2.4	22.0	3.8	14.7	5.1	22.5	7.7
Treatment p value		0.4003		0.2671		0.6333		0.4789	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.4. Soil total copper (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	647	120	605	145	774	156	675	153
	Fertilizer	611	155	576	167	760	185	649	181
	Biosolids 50	680	169	658	180	797	187	712	182
	Biosolids 100	667	164	653	171	780	176	700	173
	Biosolids 150	734	133	696	144	807	164	746	149
	Biosolids 200	697	144	634	112	789	148	407	145
	Biosolids 250	735	128	710	116	843	152	763	140
Treatment p value		0.0665		0.0678		0.6836		0.1201	
Sand	Control	1291	669	1347	736	1411	704	1350	674
	Fertilizer	1443	573	1237	487	1481	710	1387	581
	Biosolids 50	1181	506	1051	456	1266	474	1166	467
	Biosolids 100	1399	521	1358	567	1458	547	1405	523
	Biosolids 150	1375	490	1284	457	1437	542	1365	480
	Biosolids 200	1282	487	1272	554	1398	558	1317	514
	Biosolids 250	1170	357	1119	432	1306	483	1198	416
Treatment p value		0.4021		0.3262		0.8648		0.5805	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.5. Soil available copper (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	145	43	139	40	151	40	145	40
	Fertilizer	137	51	126	63	152	47	139	53
	Biosolids 50	142	41	133	51	152	42	142	44
	Biosolids 100	152	48	130	51	143	41	142	46
	Biosolids 150	140	38	123	49	142	34	135	40
	Biosolids 200	131	32	117	38	139	36	129	35
	Biosolids 250	136	37	126	41	135	36	132	37
Treatment p value		0.6012		0.5211		0.6398		0.6352	
Sand	Control	213	117	185	113	212	114	203	111
	Fertilizer	252	129	202	105	215	145	223	123
	Biosolids 50	191	114	155	78	191	89	179	92
	Biosolids 100	204	98	176	76	202	87	194	84
	Biosolids 150	182	81	170	77	179	79	177	75
	Biosolids 200	169	82	164	83	202	88	179	82
	Biosolids 250	142	53	130	45	161	71	144	57
Treatment p value		0.0223		0.1539		0.5799		0.1499	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.6. Soil total iron (%) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.83	0.10	0.65	0.08	0.75	0.10	0.74	0.12
	Fertilizer	0.84	0.11	0.69	0.12	0.75	0.11	0.76	0.12
	Biosolids 50	0.88	0.13	0.74	0.13	0.76	0.11	0.79	0.13
	Biosolids 100	0.90	0.12	0.75	0.12	0.79	0.11	0.81	0.13
	Biosolids 150	0.99	0.07	0.82	0.11	0.84	0.11	0.88	0.12
	Biosolids 200	0.99	0.11	0.81	0.07	0.86	0.08	0.89	0.12
	Biosolids 250	1.06	0.09	0.90	0.07	0.87	0.10	0.94	0.12
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	0.70	0.05	0.54	0.02	0.56	0.04	0.60	0.08
	Fertilizer	0.71	0.06	0.52	0.03	0.54	0.05	0.59	0.10
	Biosolids 50	0.68	0.04	0.52	0.04	0.54	0.03	0.58	0.08
	Biosolids 100	0.72	0.04	0.55	0.05	0.57	0.05	0.61	0.09
	Biosolids 150	0.74	0.03	0.55	0.04	0.60	0.05	0.63	0.09
	Biosolids 200	0.75	0.03	0.57	0.04	0.61	0.07	0.64	0.09
	Biosolids 250	0.77	0.03	0.62	0.05	0.64	0.04	0.68	0.08
Treatment p value		0.0002		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

D.7. Soil available iron (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	52.4	7.4	58.4	8.0	65.7	12.3	58.8	10.6
	Fertilizer	52.9	11.1	49.0	10.6	68.6	11.8	56.8	13.7
	Biosolids 50	57.5	6.1	55.0	10.7	66.4	10.2	59.7	10.1
	Biosolids 100	58.3	8.7	52.3	11.6	66.1	13.7	58.9	12.4
	Biosolids 150	67.4	9.9	53.1	11.3	75.2	6.2	65.2	12.9
	Biosolids 200	72.3	15.4	57.1	4.2	80.9	8.7	70.1	14.2
	Biosolids 250	69.0	12.2	59.6	6.3	76.1	18.0	68.2	14.3
Treatment p value		0.0006		0.2188		0.0044		0.0001	
Sand	Control	15.0	2.6	16.6	4.7	22.7	3.8	18.1	5.0
	Fertilizer	14.5	4.2	16.8	5.7	22.5	4.5	17.9	5.7
	Biosolids 50	23.8	8.2	22.4	6.7	25.4	6.6	23.8	7.0
	Biosolids 100	25.4	7.4	21.3	7.9	27.1	9.1	24.6	8.2
	Biosolids 150	33.1	5.3	27.7	8.1	28.8	8.2	29.9	7.4
	Biosolids 200	39.7	7.0	28.2	10.4	31.7	6.8	33.2	9.3
	Biosolids 250	45.6	7.3	35.6	6.3	35.5	9.3	38.9	8.8
Treatment p value		0.0001		0.0001		0.0003		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.8. Soil total manganese (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	424	43	384	42	442	52	417	50
	Fertilizer	419	42	398	79	435	50	417	48
	Biosolids 50	421	53	404	56	425	64	417	56
	Biosolids 100	420	49	403	52	434	56	419	52
	Biosolids 150	418	42	404	45	425	59	416	48
	Biosolids 200	411	48	392	31	423	53	408	45
	Biosolids 250	407	40	403	38	430	53	413	44
Treatment p value		0.6509		0.6256		0.3970		0.8859	
Sand	Control	281	14	269	9	286	13	279	14
	Fertilizer	275	14	270	17	282	19	276	17
	Biosolids 50	282	15	272	15	278	13	277	14
	Biosolids 100	277	8	266	14	275	20	273	15
	Biosolids 150	284	6	270	7	285	12	280	11
	Biosolids 200	271	7	262	9	278	17	270	13
	Biosolids 250	279	11	273	11	286	14	279	13
Treatment p value		0.2976		0.5730		0.7105		0.5216	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.9. Soil available manganese (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	1.93	0.56	1.59	0.87	1.96	0.33	1.82	0.63
	Fertilizer	1.69	0.45	1.42	0.89	2.18	0.56	1.77	0.71
	Biosolids 50	3.55	0.74	2.20	1.11	2.90	1.08	2.88	1.10
	Biosolids 100	5.44	1.12	3.18	1.36	3.30	0.06	3.97	1.48
	Biosolids 150	8.14	0.57	2.91	1.18	5.17	1.33	5.41	2.42
	Biosolids 200	9.75	2.02	5.03	1.32	6.46	2.35	7.08	2.74
	Biosolids 250	13.05	2.46	6.83	2.75	6.47	2.03	8.78	3.86
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	1.54	0.28	1.64	0.27	2.34	0.49	1.84	0.50
	Fertilizer	1.56	0.59	1.59	0.34	2.47	1.07	1.87	0.82
	Biosolids 50	2.19	0.64	2.14	0.41	2.75	0.47	2.36	0.57
	Biosolids 100	3.10	0.77	2.77	1.37	3.32	0.96	3.06	1.04
	Biosolids 150	5.08	0.99	4.43	0.97	4.51	1.15	4.67	1.04
	Biosolids 200	6.20	1.33	5.51	2.08	4.79	1.38	5.50	1.67
	Biosolids 250	9.41	1.88	8.17	2.03	6.23	1.57	7.94	2.21
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.10. Soil total molybdenum (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	38.25	4.37	28.75	7.81	36.50	6.16	34.50	7.33
	Fertilizer	35.13	4.64	36.38	7.17	34.50	7.86	32.00	7.59
	Biosolids 50	34.63	8.63	28.75	9.65	30.75	10.00	31.38	9.36
	Biosolids 100	34.25	8.01	26.75	7.98	33.25	8.55	31.42	8.53
	Biosolids 150	34.38	5.95	28.13	7.51	32.63	13.02	31.71	9.31
	Biosolids 200	30.75	6.30	23.75	5.47	27.00	5.93	27.17	6.36
	Biosolids 250	32.13	6.51	27.25	6.11	26.38	5.93	28.58	6.45
Treatment p value		0.1310		0.5711		0.0124		0.0734	
Sand	Control	21.88	8.13	16.75	7.07	17.88	6.17	18.83	7.21
	Fertilizer	21.88	5.79	17.75	7.48	17.38	6.55	19.00	6.68
	Biosolids 50	18.00	7.98	13.50	4.84	12.50	4.34	14.67	6.18
	Biosolids 100	16.25	3.73	11.88	5.49	12.38	3.93	13.50	4.70
	Biosolids 150	14.38	2.33	12.88	3.40	12.50	1.77	13.25	2.61
	Biosolids 200	14.88	3.44	12.50	4.84	11.50	2.98	12.96	3.94
	Biosolids 250	12.00	2.73	11.13	4.02	11.50	3.96	11.54	3.48
Treatment p value		0.0001		0.0051		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.11. Soil available molybdenum (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	5.13	1.15	4.76	1.94	6.69	2.29	5.52	1.97
	Fertilizer	4.78	1.58	3.84	2.15	6.03	1.96	4.88	2.04
	Biosolids 50	4.35	1.98	3.80	2.30	4.67	2.16	2.47	2.09
	Biosolids 100	4.10	1.41	2.78	1.03	5.10	2.02	3.99	1.76
	Biosolids 150	4.22	1.20	2.93	1.48	5.03	1.67	4.06	1.65
	Biosolids 200	3.62	0.95	2.70	1.56	3.91	0.89	3.41	1.24
	Biosolids 250	3.93	1.15	3.07	1.55	3.41	1.34	3.47	1.35
Treatment p value		0.2735		0.0715		0.0023		0.0129	
Sand	Control	0.24	0.07	0.24	0.06	0.21	0.09	0.23	0.08
	Fertilizer	0.25	0.07	0.24	0.05	0.20	0.12	0.23	0.09
	Biosolids 50	0.24	0.07	0.19	0.04	0.12	0.06	0.18	0.07
	Biosolids 100	0.26	0.07	0.21	0.02	0.19	0.11	0.22	0.08
	Biosolids 150	0.26	0.04	0.19	0.03	0.18	0.08	0.21	0.07
	Biosolids 200	0.26	0.06	0.20	0.04	0.22	0.08	0.23	0.06
	Biosolids 250	0.32	0.07	0.22	0.05	0.20	0.08	0.25	0.08
Treatment p value		0.1096		0.0545		0.1652		0.1601	

N = 8 for each year and 24 for mean
SD = standard deviation

Table D.12. Soil total zinc (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	14.8	3.9	18.9	2.0	22.6	6.9	18.8	5.6
	Fertilizer	13.6	1.9	19.9	5.0	21.9	3.0	18.5	4.9
	Biosolids 50	52.3	19.9	59.4	27.8	65.3	27.3	59.0	24.7
	Biosolids 100	78.5	24.6	81.4	32.5	94.5	43.2	84.8	33.5
	Biosolids 150	148.1	26.8	136.3	57.3	124.8	39.9	136.4	42.4
	Biosolids 200	166.3	23.4	131.5	41.5	155.8	39.8	151.2	37.4
	Biosolids 250	213.8	49.6	184.1	44.6	163.8	30.9	187.2	45.6
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	8.3	6.9	14.3	3.7	15.3	2.3	12.6	5.5
	Fertilizer	5.8	2.1	13.4	2.6	14.6	3.3	11.3	4.8
	Biosolids 50	35.5	10.6	31.1	7.7	34.9	17.2	33.8	12.1
	Biosolids 100	49.6	18.9	51.0	28.6	50.6	16.8	50.4	21.1
	Biosolids 150	80.3	13.6	70.4	21.7	78.9	20.1	76.5	18.5
	Biosolids 200	120.4	31.8	87.3	29.0	92.5	23.5	100.0	30.9
	Biosolids 250	180.1	46.4	141.9	48.2	125.1	29.6	149.0	46.7
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.13. Soil available zinc (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	0.71	0.13	2.43	3.30	2.51	1.43	1.88	2.16
	Fertilizer	0.81	0.32	2.40	2.73	2.47	1.22	1.89	1.83
	Biosolids 50	6.79	1.54	5.56	4.43	11.86	7.95	8.07	5.80
	Biosolids 100	13.93	2.80	10.90	4.60	13.76	5.73	12.86	4.56
	Biosolids 150	22.28	4.63	9.57	4.71	28.52	13.22	20.12	11.46
	Biosolids 200	26.01	6.20	16.17	5.88	32.11	14.98	24.76	11.64
	Biosolids 250	33.65	9.44	23.40	8.98	32.98	11.93	30.01	10.85
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	0.43	0.07	0.71	0.26	1.03	0.33	0.72	0.34
	Fertilizer	0.54	0.20	0.97	0.50	2.92	5.53	1.48	3.24
	Biosolids 50	5.88	1.84	4.98	1.81	5.93	3.18	5.60	2.30
	Biosolids 100	10.06	2.66	6.97	5.73	9.38	5.37	8.80	4.77
	Biosolids 150	17.15	2.01	14.40	4.41	14.50	5.94	15.35	4.43
	Biosolids 200	21.01	4.79	17.24	6.49	16.25	7.63	18.17	6.47
	Biosolids 250	32.33	6.95	26.78	11.62	23.40	8.75	27.50	9.65
Treatment p value		0.0001		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.14. Soil total chromium (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	32.5	6.9	9.4	4.1	18.4	4.4	20.1	11.0
	Fertilizer	33.3	9.4	10.0	4.4	19.4	5.3	20.9	11.7
	Biosolids 50	36.9	9.0	14.5	8.7	17.5	3.3	23.0	12.4
	Biosolids 100	39.0	7.8	10.8	3.4	22.8	11.6	24.2	14.3
	Biosolids 150	37.3	12.6	15.4	6.3	47.4	66.9	33.3	40.1
	Biosolids 200	39.4	12.4	13.6	5.1	24.8	4.7	25.9	13.3
	Biosolids 250	41.1	10.6	16.4	3.3	22.3	2.5	26.6	12.5
Treatment p value		0.2030		0.0130		0.2881		0.1036	
Sand	Control	81.4	8.9	31.4	15.5	34.9	3.6	49.2	25.4
	Fertilizer	81.6	16.3	27.4	12.1	29.1	4.4	46.0	28.1
	Biosolids 50	75.0	11.6	19.4	5.9	27.6	4.1	40.7	26.2
	Biosolids 100	73.5	13.6	22.5	7.7	34.0	7.2	43.3	24.2
	Biosolids 150	72.5	11.6	26.0	4.8	35.1	6.0	44.5	21.9
	Biosolids 200	74.3	10.0	25.4	5.2	37.9	5.4	45.8	22.3
	Biosolids 250	62.0	9.7	30.0	3.7	37.3	3.5	43.1	15.2
Treatment p value		0.0139		0.1257		0.0002		0.0492	

N = 8 for each year and 24 for mean

SD = standard deviation

Table D.15. Soil total nickel (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	-	-	4.63	1.30	6.50	0.93	5.56	2.49
	Fertilizer	-	-	5.25	1.67	5.50	1.20	5.38	2.39
	Biosolids 50	-	-	7.25	1.39	6.25	1.04	6.75	2.96
	Biosolids 100	-	-	6.13	1.81	7.13	1.13	6.63	2.98
	Biosolids 150	-	-	8.25	2.66	8.50	1.31	8.38	3.91
	Biosolids 200	-	-	8.63	1.60	9.13	1.36	8.88	3.97
	Biosolids 250	-	-	9.13	1.25	9.13	1.46	9.13	4.05
Treatment p value				0.0001		0.0001		0.0001	
Sand	Control	-	-	2.50	1.20	2.88	0.99	2.69	1.19
	Fertilizer	-	-	2.38	0.92	2.38	0.92	2.38	0.97
	Biosolids 50	-	-	2.75	0.71	3.00	1.31	2.88	1.22
	Biosolids 100	-	-	3.63	1.60	2.75	1.16	3.19	1.56
	Biosolids 150	-	-	4.50	1.60	4.00	1.60	4.25	2.01
	Biosolids 200	-	-	4.38	0.92	4.38	0.74	4.38	1.75
	Biosolids 250	-	-	5.13	1.81	5.00	1.31	5.06	2.31
Treatment p value				0.0001		0.0001		0.0001	

N = 8 for each year and 16 for mean

SD = standard deviation

No data for 1998

Table D.16. Soil total lead (ppm) means at a depth of 0 to 15 cm for 1998, 1999 and 2000.

Site	Treatment	1998	SD	1999	SD	2000	SD	Mean of Years	SD
Silt Loam	Control	3.00	1.07	2.14	0.48	9.88	2.95	5.01	3.94
	Fertilizer	3.25	1.04	2.57	0.72	11.25	2.66	5.69	4.34
	Biosolids 50	7.00	2.83	6.90	3.89	13.75	4.10	9.22	4.78
	Biosolids 100	9.50	2.56	7.72	3.13	17.50	4.24	11.57	5.42
	Biosolids 150	17.75	4.33	13.86	5.38	19.25	5.34	16.95	5.34
	Biosolids 200	20.00	3.70	13.61	5.56	22.00	7.69	18.54	6.70
	Biosolids 250	24.75	6.32	17.72	5.99	24.13	4.49	22.20	6.30
Treatment p value		0.0001		0.0001		0.0001		0.0001	
Sand	Control	6.00	6.14	2.00	0.00	5.00	1.77	4.33	3.93
	Fertilizer	5.25	5.65	2.00	0.00	6.75	2.43	4.67	3.95
	Biosolids 50	4.50	3.51	2.57	1.04	6.50	1.93	4.52	2.81
	Biosolids 100	5.50	6.12	4.50	2.04	8.50	3.21	6.17	4.34
	Biosolids 150	7.50	3.66	6.25	2.87	12.13	2.90	8.63	3.98
	Biosolids 200	11.25	6.67	7.54	2.99	11.00	4.93	9.93	5.16
	Biosolids 250	11.00	8.00	12.83	5.01	16.63	5.76	13.48	6.55
Treatment p value		0.1243		0.0001		0.0001		0.0001	

N = 8 for each year and 24 for mean

SD = standard deviation.

APPENDIX E
Additional Data Tables For Chapter IV

Table E.1. Vegetation composition by % cover and bare ground for 1999.

Site	Treatment	Pubescent Wheatgrass	Orchard Grass	Creeping Red Fescue	Russian Wild Ryegrass	Alfalfa	Alsike Clover	Other	Bare Ground
Silt Loam	Control	1.3	4.9	1.8	0.0	3.0	0.2	0.0	88.8
	Fertilizer	2.3	8.1	3.4	0.0	7.5	0.8	0.0	78.0
	Biosolids 50	4.2	38.0	3.8	0.0	23.4	5.4	0.9	24.4
	Biosolids 100	2.4	34.0	1.5	0.0	32.0	8.3	6.1	15.8
	Biosolids 150	8.3	24.4	1.9	0.0	40.6	11.1	1.9	11.9
	Biosolids 200	4.7	20.5	0.3	0.0	42.3	9.6	8.9	13.5
	Biosolids 250	5.4	18.1	1.4	0.0	48.0	10.0	6.8	10.4
Treatment p value		0.2805	0.0001	0.0194	-	0.0001	0.0001	0.0555	0.0001
Sand	Control	0.0	0.0	0.2	0.0	0.0	0.0	0.0	99.7
	Fertilizer	0.2	0.5	0.0	0.0	0.3	0.0	0.0	99.0
	Biosolids 50	2.7	1.9	0.4	0.0	5.3	0.6	0.1	89.1
	Biosolids 100	6.0	1.9	0.2	0.0	4.7	0.8	0.1	86.3
	Biosolids 150	5.0	1.8	0.6	0.0	10.6	0.8	0.0	81.3
	Biosolids 200	6.5	4.9	1.0	0.0	10.5	1.6	0.5	75.1
	Biosolids 250	10.9	4.3	1.0	0.0	14.3	1.6	1.0	67.1
Treatment p value		0.0001	0.0001	0.0492	-	0.0001	0.0023	0.3456	0.0001

N = 8 for each year at each site

SD = standard deviation

Table E.2. Frequency of species (%) for 1999.

Site	Treatment	Pubescent Wheatgrass	Orchard Grass	Creeping Red Fescue	Russian Wild Ryegrass	Alfalfa	Alsike Clover	Other
Silt Loam	Control	60.0	55.0	57.5	0.0	57.5	7.5	2.5
	Fertilizer	55.0	72.5	42.5	0.0	67.5	15.0	0.0
	Biosolids 50	42.5	67.5	45.0	0.0	67.5	32.5	2.5
	Biosolids 100	40.0	75.0	35.0	0.0	67.5	30.0	15.0
	Biosolids 150	47.5	55.0	52.5	0.0	72.5	52.5	0.0
	Biosolids 200	50.0	60.0	40.0	0.0	82.5	47.5	2.5
	Biosolids 250	57.5	80.0	30.0	0.0	77.5	30.0	2.5
Treatment p value		0.0892	0.0879	0.2897	-	0.4438	0.0005	0.0568
Sand	Control	5.0	2.5	17.5	0.0	0.0	0.0	0.0
	Fertilizer	20.0	12.5	5.0	0.0	15.0	0.0	2.5
	Biosolids 50	42.5	25.0	15.0	0.0	45.0	7.5	2.5
	Biosolids 100	40.0	20.0	10.0	0.0	37.5	15.0	2.5
	Biosolids 150	40.0	22.5	20.0	0.0	52.5	15.0	0.0
	Biosolids 200	55.0	40.0	20.0	0.0	52.5	20.0	0.0
	Biosolids 250	52.5	40.0	17.5	0.0	60.0	20.0	7.5
Treatment p value		0.0013	0.0012	0.6037	-	0.0001	0.0003	0.1332

N = 8 for each year at each site

SD = standard deviation

Table E.3. Frequency of species (%) for 2000.

Site	Treatment	Pubescent Wheatgrass	Orchard Grass	Creeping Red Fescue	Russian Wild Ryegrass	Alfalfa	Alsike Clover	Other
Silt Loam	Control	0.0	37.5	62.5	0.0	20.0	7.5	2.5
	Fertilizer	10.0	62.5	67.5	0.0	37.5	10.0	15.0
	Biosolids 50	47.5	77.5	12.5	0.0	25.0	37.5	15.0
	Biosolids 100	35.0	70.0	5.0	0.0	20.0	22.5	15.0
	Biosolids 150	65.0	60.0	2.5	0.0	37.5	20.0	5.0
	Biosolids 200	57.5	57.5	0.0	0.0	30.0	22.5	7.5
	Biosolids 250	70.0	42.5	0.0	0.0	47.5	10.0	5.0
Treatment p value		0.0001	0.0053	0.0001	-	0.0249	0.0789	0.3761
Sand	Control	0.0	2.5	25.0	0.0	2.5	0.0	0.0
	Fertilizer	7.5	7.5	25.0	0.0	12.5	0.0	0.0
	Biosolids 50	57.5	7.5	27.5	0.0	22.5	0.0	2.5
	Biosolids 100	60.0	2.5	5.0	0.0	47.5	2.5	7.5
	Biosolids 150	45.0	5.0	22.5	0.0	52.5	2.5	55.0
	Biosolids 200	60.0	7.5	2.5	0.0	45.0	0.0	72.5
	Biosolids 250	72.5	5.0	15.0	0.0	55.0	0.0	67.5
Treatment p value		0.0001	0.9277	0.0820	-	0.0001	0.4381	0.0972

N = 8 for each year at each site

SD = standard deviation

Table E.4. Mean height (cm) of all plant species per treatment for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	3.57	1.53	13.79	12.27
	Fertilizer	4.88	2.02	21.60	12.87
	Biosolids 50	16.89	8.47	135.63	11.30
	Biosolids 100	21.68	10.47	130.00	11.17
	Biosolids 150	20.33	11.10	122.75	15.16
	Biosolids 200	22.50	6.82	126.13	14.73
	Biosolids 250	22.84	8.51	126.93	10.40
Treatment p value		0.0001		0.0001	
Sand	Control	0.50	0.47	2.98	2.67
	Fertilizer	0.71	0.80	7.14	7.15
	Biosolids 50	2.51	2.08	55.85	18.71
	Biosolids 100	2.92	1.41	66.53	8.08
	Biosolids 150	3.95	2.44	57.63	12.12
	Biosolids 200	5.32	11.64	57.33	15.47
	Biosolids 250	6.34	3.34	55.28	8.49
Treatment p value		0.0001		0.0001	

N = 8 for each year at each site

SD = standard deviation

Table E.5. Plant tissue calcium (%) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	1.10	0.83
	Fertilizer	-	-	1.58	0.71
	Biosolids 50	1.37	0.63	0.66	0.24
	Biosolids 100	1.60	0.63	0.81	0.37
	Biosolids 150	1.80	0.80	1.13	0.44
	Biosolids 200	2.00	0.86	0.87	0.25
	Biosolids 250	2.10	0.77	1.14	0.42
	Treatment p value	0.0001		0.0020	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	2.47	0.64	1.48	0.72
	Biosolids 100	2.83	0.86	1.80	0.54
	Biosolids 150	4.03	0.61	2.46	0.41
	Biosolids 200	3.59	0.87	2.05	0.57
	Biosolids 250	2.53	0.55	2.26	0.34
	Treatment p value	0.0003		0.0065	

N = 8 for each year at each site

SD = standard deviation

Table E.6. Plant tissue magnesium (%) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	0.193	0.031
	Fertilizer	-	-	0.238	0.056
	Biosolids 50	0.306	0.039	0.200	0.043
	Biosolids 100	0.346	0.029	0.223	0.048
	Biosolids 150	0.346	0.031	0.256	0.049
	Biosolids 200	0.353	0.050	0.220	0.035
	Biosolids 250	0.375	0.072	0.243	0.041
Treatment p value		0.0244		0.0072	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	0.389	0.068	0.254	0.068
	Biosolids 100	0.426	0.050	0.263	0.065
	Biosolids 150	0.495	0.083	0.331	0.042
	Biosolids 200	0.468	0.071	0.314	0.055
	Biosolids 250	0.375	0.048	0.324	0.032
Treatment p value		0.0034		0.0135	

N = 8 for each year at each site

SD = standard deviation

Table E.7. Plant tissue sulfur (%) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	0.25	0.09
	Fertilizer	-	-	0.28	0.05
	Biosolids 50	0.36	0.04	0.20	0.04
	Biosolids 100	0.39	0.13	0.23	0.06
	Biosolids 150	0.33	0.04	0.26	0.03
	Biosolids 200	0.34	0.03	0.24	0.03
	Biosolids 250	0.35	0.04	0.26	0.04
	Treatment p value	0.3786		0.0500	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	0.42	0.10	0.23	0.05
	Biosolids 100	0.38	0.04	0.25	0.04
	Biosolids 150	0.34	0.01	0.27	0.05
	Biosolids 200	0.33	0.03	0.28	0.03
	Biosolids 250	0.31	0.04	0.29	0.03
	Treatment p value	0.0017		0.0184	

N = 8 for each year at each site

SD = standard deviation

Table E.8. Plant tissue boron (ppm) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	27.87	22.17
	Fertilizer	-	-	59.51	21.22
	Biosolids 50	65.86	5.07	20.27	3.11
	Biosolids 100	88.33	63.61	21.08	3.11
	Biosolids 150	70.53	4.33	22.13	3.79
	Biosolids 200	74.59	8.58	22.64	2.58
	Biosolids 250	78.66	10.38	25.39	4.20
Treatment p value		0.5560		0.0001	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	74.81	11.14	32.14	12.61
	Biosolids 100	83.03	12.34	36.67	7.53
	Biosolids 150	94.17	7.05	41.59	4.97
	Biosolids 200	77.40	32.20	41.86	11.23
	Biosolids 250	79.49	12.70	40.69	7.51
Treatment p value		0.2301		0.1914	

N = 8 for each year at each site

SD = standard deviation

Table E.9. Plant tissue manganese (ppm) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	126.43	22.77
	Fertilizer	-	-	154.38	25.52
	Biosolids 50	112.25	14.01	122.63	28.03
	Biosolids 100	137.75	26.32	147.75	36.90
	Biosolids 150	158.25	13.44	166.00	39.80
	Biosolids 200	179.75	12.30	158.88	23.19
	Biosolids 250	209.50	43.67	205.13	52.12
	Treatment p value	0.0001		0.0006	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	146.38	30.91	134.00	37.55
	Biosolids 100	182.50	32.35	171.63	39.77
	Biosolids 150	289.75	209.42	203.38	18.99
	Biosolids 200	270.13	45.41	208.13	32.30
	Biosolids 250	228.13	89.08	235.38	29.29
	Treatment p value	0.0313		0.0001	

N = 8 for each year at each site
SD = standard deviation

Table E.10. Plant tissue zinc (ppm) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	36.86	13.06
	Fertilizer	-	-	53.75	22.03
	Biosolids 50	59.00	7.09	37.63	8.88
	Biosolids 100	66.75	13.72	45.38	11.24
	Biosolids 150	71.63	6.72	59.88	12.97
	Biosolids 200	87.13	7.32	56.00	6.26
	Biosolids 250	102.00	23.64	69.88	10.31
Treatment p value		0.0001		0.0001	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	71.86	24.27	52.50	20.44
	Biosolids 100	86.75	14.07	85.38	41.04
	Biosolids 150	131.38	39.99	91.63	11.86
	Biosolids 200	140.25	23.94	89.75	22.19
	Biosolids 250	134.38	41.29	101.63	10.21
Treatment p value		0.0001		0.0027	

N = 8 for each year at each site
SD = standard deviation

Table E.11. Plant tissue iron (%) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	0.02	0.01
	Fertilizer	-	-	0.02	0.01
	Biosolids 50	0.01	0.01	0.01	0.00
	Biosolids 100	0.02	0.02	0.01	0.00
	Biosolids 150	0.01	0.00	0.01	0.00
	Biosolids 200	0.01	0.01	0.01	0.00
	Biosolids 250	0.02	0.01	0.02	0.01
	Treatment p value	0.7596		0.0673	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	0.02	0.02	0.01	0.01
	Biosolids 100	0.02	0.01	0.02	0.02
	Biosolids 150	0.02	0.01	0.01	0.01
	Biosolids 200	0.02	0.01	0.02	0.02
	Biosolids 250	0.01	0.00	0.01	0.00
	Treatment p value	0.5017		0.6893	

N = 8 for each year at each site

SD = standard deviation

Table E.12. Plant tissue nickel (ppm) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	5.86	11.54
	Fertilizer	-	-	2.50	3.46
	Biosolids 50	1.00	0.00	1.13	0.35
	Biosolids 100	1.00	0.00	1.13	0.35
	Biosolids 150	1.00	0.00	1.50	1.07
	Biosolids 200	1.00	0.00	1.38	0.52
	Biosolids 250	1.00	0.00	1.63	0.74
	Treatment p value	n/a		0.3756	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	5.88	9.70	1.75	1.16
	Biosolids 100	5.00	5.61	2.88	2.03
	Biosolids 150	2.25	1.04	3.00	1.93
	Biosolids 200	1.75	1.75	3.00	1.77
	Biosolids 250	1.50	1.07	3.38	1.69
	Treatment p value	0.2974		0.2287	

N = 8 for each year at each site

SD = standard deviation

Table E.13. Plant tissue lead (ppm) concentration for 1999 and 2000.

Site	Treatment	1999 Mean	SD	2000 Mean	SD
Silt Loam	Control	-	-	2.00	0.00
	Fertilizer	-	-	2.50	0.93
	Biosolids 50	2.00	0.00	2.00	0.00
	Biosolids 100	2.00	0.00	2.25	0.71
	Biosolids 150	2.00	0.00	2.25	0.71
	Biosolids 200	2.00	0.00	2.75	1.04
	Biosolids 250	2.00	0.00	2.25	0.71
	Treatment p value	n/a		0.3704	
Sand	Control	-	-	-	-
	Fertilizer	-	-	-	-
	Biosolids 50	2.63	1.60	2.00	0.00
	Biosolids 100	2.25	0.71	2.00	0.00
	Biosolids 150	2.25	0.71	2.00	0.00
	Biosolids 200	5.63	10.25	3.75	4.95
	Biosolids 250	2.38	0.74	2.00	0.00
	Treatment p value	0.5229		0.4241	

N = 8 for each year at each site
SD = standard deviation